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CPAR-CHL-98-1
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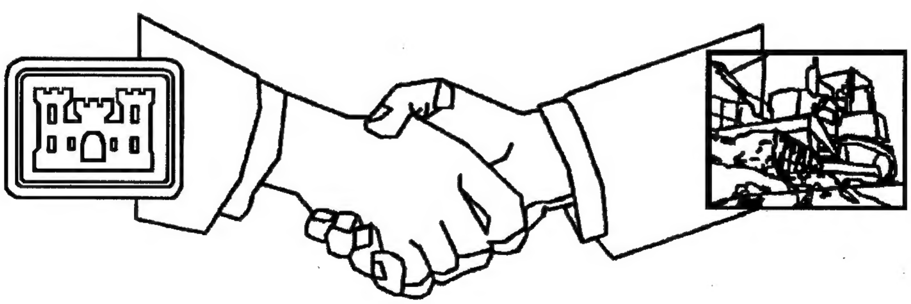
CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Field Evaluation/Demonstration of a Multisegmented Dewatering System for Accreting Beach Sand in a High-Wave-Energy Environment

by

William R. Curtis, Jack E. Davis



A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

Technical Report
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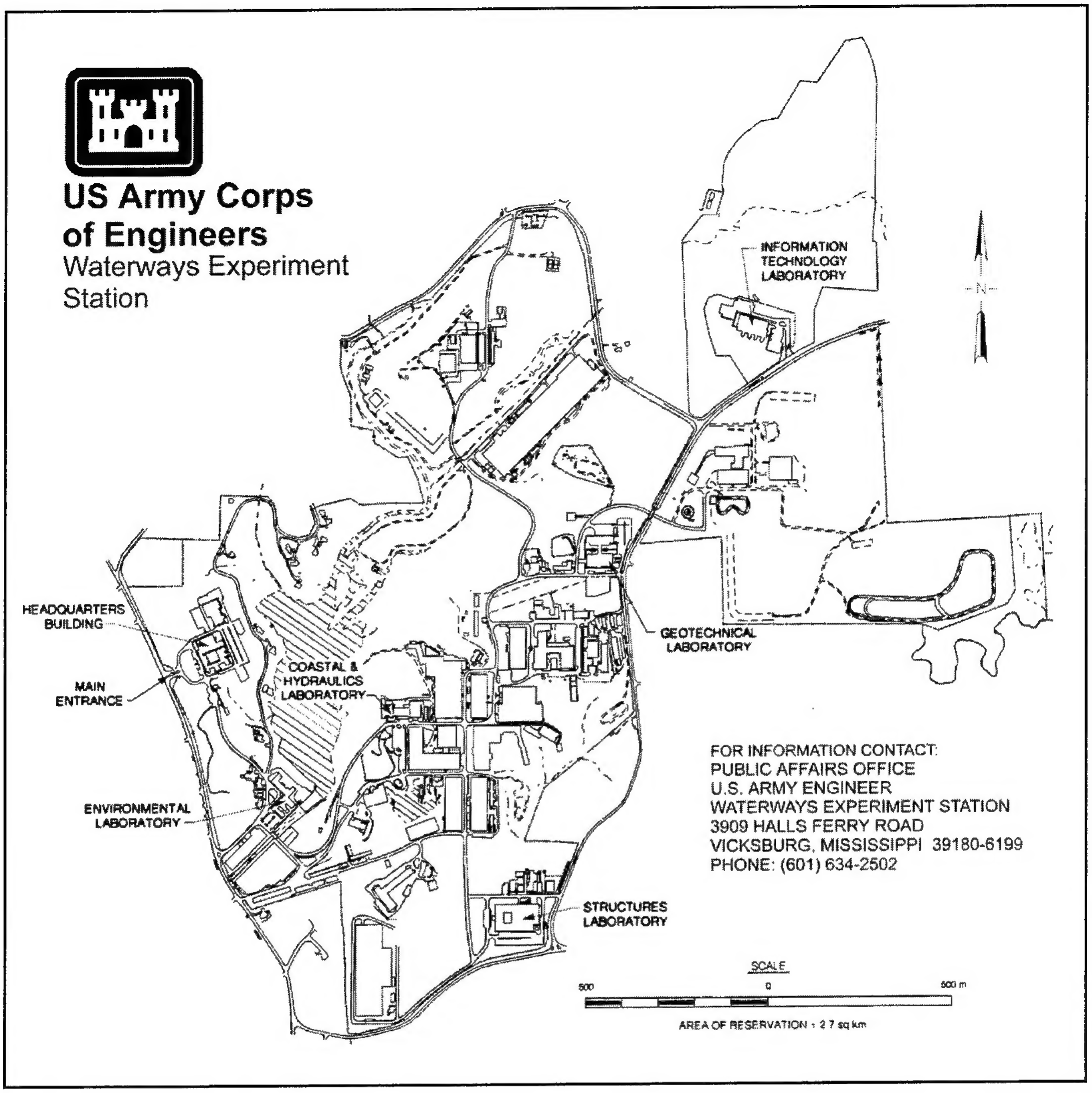

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Preface

This investigation, as outlined in the Construction Productivity Advancement Research (CPAR) Program Cooperative Research and Development Agreement (CPAR-CRDA), focused on the collection of field measurements of coastal processes and system parameters at an operational beach dewatering project in a high-wave-energy environment. Collected data were used to evaluate dewatering technology as a viable alternative for coastal shoreline stabilization and coastal storm damage mitigation.

The investigation described herein was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), by the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), as part of the CPAR Program. The industry partner for this study was the Siasconset Beach Preservation Fund (SBPF), Nantucket, MA. SBPF contracted with Coastal Stabilization, Inc. (CSI), Rockaway, NJ, to perform a portion of the industry partner's work effort. The HQUSACE Technical Monitors were Messrs. Brad James and John Lockhart.

Separate investigations were sponsored by WES and SBPF in order to meet study objectives. The WES investigation was under the general supervision of Dr. James R. Houston, Director, CHL, Mr. Charles C. Calhoun, Jr., Assistant Director, CHL, and Mr. Thomas W. Richardson, Chief, Engineering Development Division (EDD), CHL. Direct supervision was provided by Ms. Joan Pope, Chief, Coastal Structures and Evaluation Branch (CSE), EDD, and Dr. Yen-hsi Chu, Chief, Engineering Applications Unit (EAU), CSE. Technical assistance in the WES investigation was provided by Dr. Ian L. Turner, University of New South Wales, Sydney, Australia; Messrs. Monroe B. Savage and Lewis B. Smithhart, Information Technology Laboratory (ITL), WES; Mr. Kent Hathaway, Field Research Facility, EDD, WES; and Messrs. Scott Bourne and Robert Chain, Dyntel, Vicksburg, MS. The SBPF investigation was under the general and direct supervision of Messrs. F. Helmut Weymar and Kermit Roosevelt. Mr. William F. McCleese was the CPAR point of contact at WES. This report is the final report for the CPAR project entitled "A Field Test/Demonstration of a Multi-Segmented Dewatering System for Accreting Beach Sand in a High Wave Energy Environment," and was prepared by WES investigators Messrs. William R. Curtis and Jack E. Davis, CSE, EDD.

Mr. Douglas W. Mann, Coastal Planning and Engineering, Inc. (CP&E), Boca Raton, FL, prepared Appendix A.

Beach dewatering system design, construction, and operational and geotechnical data were provided by Mr. Robert G. Kunzel, CSI. In cooperation with SBPF, pre-project field characterization data were provided by Dr. Frank Fessenden, Bentley College, Waltham, MA; Mr. Leo Asadoorian, Blackwell and Associates, Inc., Nantucket, MA; and Mr. Kim Beechler, CP&E.

During the publication of this report, Dr. Robert W. Whalin was the Director of WES. COL Robin R. Cababa, EN, was the Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
miles	0.6214	kilometers
gallons/minute	15.853	liters/second
gallons/minute/foot	4.833	liters/second/meter
feet	3.281	meters
miles/hour	2.237	meters/second

Summary Description of Research and Development Partnership

In March 1995, the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and the Siasconset Beach Preservation Fund (SBPF), Nantucket, MA, entered into a Construction Productivity Advancement Research (CPAR)-Cooperative Research and Development Agreement (CRDA). The objective under this agreement was to demonstrate use of a multi-segmented dewatering system for accreting beach sand in a high wave-energy environment.

This research was conducted jointly by WES and SBPF. SBPF contracted with Coastal Stabilization, Inc. (CSI), Rockaway, NJ, for the design, construction, installation, and operational maintenance of the dewatering systems. CSI is the U.S. patent holder for beach-face dewatering technology and has developed a beach-face dewatering product named STABEACH™. SBPF and CSI engaged several other contractors to provide support in the construction and maintenance of the systems.

1 Introduction

Background

Cost-effective shoreline stabilization methods are of benefit to managers of public and private coastal properties. When effective shoreline stabilization is applied, benefits may be claimed due to protection of property and infrastructure from coastal flooding and storm wave impact. Depending on the methodology applied, recreational and habitat enhancement benefits may also be claimed. The concept of beach dewatering technology used to accrete beach sand or minimize coastal erosion was developed to function as a cost-effective shoreline stabilization method. However, the functionality of operational prototype-scale beach dewatering systems has yet to be objectively evaluated. Joint interest in the area of coastal shoreline stabilization resulted in a Construction Productivity Advancement Research (CPAR)-Cooperative Research and Development Agreement (CRDA) between the U.S. Army Engineer Waterways Experiment Station (WES) and the Siasconset Beach Preservation Fund (SBPF).

Objectives

Specific objectives of this research were to (a) authoritatively document the use of a multi-segmented beach dewatering system to accrete beach sand and minimize erosion, and (b) develop quantitative guidance for constructing and operating beach dewatering installations.

Approach

The approach taken during this study to meet the objectives given above was to operate, maintain, and repair the dewatering systems, monitor the operational characteristics of the dewatering systems, and monitor beach and nearshore characteristics to determine the influence of the dewatering systems on beach development.

Evaluations were made of pre-project data collected by independent engineering consultants during the development of the project to characterize the

environment and identify the existing conditions. Quarterly wading surveys of beach transects (from the toe of the bluff to wading depth of water) were conducted. The transects were distributed over the shoreline including both dewatering system reaches and control areas. Approximately 40 transects were used. Offshore hydrographic surveys were conducted semiannually to show the changes in the shoreline position, beach slope, and volume of accretion and erosion in the regions where the dewatering systems are deployed and the adjacent control beaches. Aerial photographs were taken quarterly to assess beach width changes and the influence of the combined systems on the shoreline. Transects of groundwater taps were established at one of the dewatering systems and a control area to relate the dewatering system operational parameters, tide levels, wave conditions, and sediment characteristics to the variation of the local water table. A video imaging system capable of approximately quantifying beach changes, wave conditions, and other parameters within its field of view was installed at one system location. The video system provided hourly images of the beach area. The video images provided information about any changes that occurred along the beach between quarterly monitoring efforts.

The data were studied to determine the extent of the dewatering systems' influence on the beach over both short or long time periods and the results of the study were disseminated through a variety of technical exchange forums and media.

The remainder of this report reviews the results from previous laboratory and field experiments, and prototype installations of beach groundwater manipulation techniques. The Nantucket sites and resulting system designs are characterized. The monitoring program and pertinent data analyses are discussed covering the physical characteristics of the system and beach response, as well as the results of environmental impact measurements. The report then provides some conclusions and recommendations for future research, commercialization, marketing, and implementation of the technology.

Previous Studies

According to the detailed literature review reported by Turner and Leatherman (in preparation), the origin of the beach dewatering concept can be traced back to landmark coastal research investigations conducted in the 1940's. In the work of Bagnold (1940), laboratory experiments were described in which the infiltration of wave uprush on the beach face was inhibited, resulting in a more energetic backrush. Bagnold's experiments implied that with enhanced infiltration of wave uprush on the beach face, onshore transport of sediment may be facilitated while the offshore transport of sediment is reduced. In the work of Grant (1946, 1948), it was qualitatively documented that the beach water table can have a significant influence on the morphological dynamics of the shoreline. Grant concluded that a permeable beach with a low water table is more stable than a beach with a high water table. For a beach with a low water table, waves uprushing in the active swash zone rapidly infiltrate the permeable beach above

the unsaturated beach-water table interface. This infiltration results in a reduction of wave uprush velocity and backrush velocity. As velocities drop below a critical value for transport of the beach sediment, deposition of sediment entrained in the wave uprush occurs. With continued infiltration, reduced velocities facilitate sediment deposition and reduce seaward transport of sediment with wave backrush. Grant also concluded that backrush velocities may be enhanced below the active seepage face of the groundwater outcrop, as groundwater discharge is added to the wave backrush.

Emery and Foster (1948) conducted field surveys of beach groundwater, investigating the relationship between the elevation of the beach groundwater and the phase of the tide. Emery and Foster observed that, as the tide began to flood, the beach groundwater outcrop on the foreshore of the profile became elevated. Similarly, the groundwater outcrop dropped in elevation following the onset of the tidal ebb. Emery and Foster also noted that, with the falling tide, groundwater discharge was observed, aiding sediment erosion at the beach toe. Following up on insight gained from previous researchers, Duncan (1964) investigated the cyclic patterns of beach-face erosion and accretion as influenced by the tide. Duncan confirmed the concepts of his predecessors. With a flooding tide and elevated groundwater, the infiltration of wave uprush was inhibited until the uprush advanced over the unsaturated beach, depositing sediment at the top of the foreshore profile. On the ebb tide, the elevation of the groundwater outcrop lagged behind the ocean-water elevation leaving a subaerial, yet saturated, beach face. Limited wave backrush infiltrated during the ebb tidal phase. The motion of the groundwater discharge functioned to reduce the threshold for incipient particle motion of the sand during the wave backrush, aiding foreshore erosion.

Since the 1940's, the influence of groundwater elevation on swash zone dynamics and subsequent erosion and accretion of the beach face has been investigated in the laboratory and field. However, the interactions between beach groundwater, swash dynamics, and sediment transport quantitatively remain poorly understood. Although sediment transport processes in the swash zone remain poorly understood, decades of research have confirmed that the influence of beach groundwater can be significant to the erosion and accretion of sediment on the foreshore region of the beach profile.

Machemehl, French, and Huang (1975) conducted the first experimental test of engineered artificial manipulation of beach groundwater. In a two-dimensional wave flume with varying monochromatic wave heights, the investigators lowered the elevation of the beach groundwater by means of a polyvinyl chloride (PVC) drain installed in a shore-parallel orientation. The objective of the experiment was to study the drain's effect on the foreshore accretion. They observed that beach drainage greatly enhanced the rate of sediment deposition on the foreshore and accelerated the rate of profile recovery following an erosive event. Kawata and Tschuiya (1986) observed similar results when applying a sub-sand filter system to induce foreshore stability in a wave flume. Accretion of beach material occurred on the drained beach for both solitary and monochromatic waves.

Other laboratory investigations addressing the effect of groundwater manipulation on foreshore sediment transport processes have been published in the literature and include the work of Sato (1990); Ogden and Weisman (1991); Herrington (1993); Sato, Hata, and Fukushima (1994); Weisman, Seidel, and Ogden (1995); and Kanazawa et al. (1997). Generally, laboratory simulation of beach face drainage has enhanced sediment accretion on the beach face under varying wave conditions and under tidal and nontidal conditions. To date, all laboratory experimentation has produced only a qualitative measure of beach profile response to artificial manipulation of the groundwater. Profile response and operational parameter measurements derived from small-scale physical model experiments cannot be scaled from wave flume to prototype (Sato et al. 1997). Turner and Leatherman (in preparation) caution that wave flume experimentation does not represent the unconfined aquifer existing below many natural beaches. Rather, the physical model experiments depict the beaches as a thin veneer of beach material superimposed on an impermeable surface. The degree to which the "unnatural" underlying impermeable layer contributes to accelerated seaward transport of sediment during undrained model tests cannot be determined.

The application of beach dewatering technology in the field has taken several forms. Chappel et al. (1979) first made the transition from the laboratory to prototype scale, as a series of mechanical beach dewatering wells were installed on the southern coast of New South Wales, Australia. Chappel et al. report qualitative evidence that the accretion of beach material on the foreshore of the profile can be induced by lowering the near-coast groundwater elevation. Due to the highly dynamic shoreline, the investigators were unable to quantify the influence of the wells on the morphologic response of the beach.

In 1981, the Danish Geotechnical Institute (DGI) installed a water filtration system in the beach at Hirtshals in Torsminde, on the northern coast of Denmark (Vesterby 1991; Ovesen and Schuldt 1992; Schuldt 1992a; Vesterby 1994). The filtration system was designed to pump seawater from below the swash zone to provide water for heat pumps and aquaria located at the Danish North Sea Research Center (DNRC). The filtration system pumped approximately 400 m^3/hr, and originally consisted of a 200-m section of 0.2- to 0.3-m perforated PVC pipe buried in a shore-parallel orientation 2.5 m below mean sea level (MSL) 5 m landward of the shoreline. Following 6 months of operation, the volume of water supplied to the DNRC by the filtration system discharge pumps was substantially reduced. A site inspection of the beach revealed that the shoreline in the vicinity of the drain pipe had prograded 20 to 30 m seaward, lengthening the filter path and subsequently decreasing discharge yield by 40 percent. To increase discharge, a second 220-m drain line was installed as an extension of the first. The result of the extension was that the shoreline, composed of well-sorted, medium-grain sand, in the vicinity of the horizontal wells prograded seaward, even during the winter storm season. In 1983, a second site (termed Hirtshals East) was chosen by DGI to field test the effect of beach dewatering on shoreline response and was located 1 km from the DNRC site. A 200-m drain pipe was installed in a beach composed of mixed fine-grained sand, silt, and clay. The Hirtshals East project was terminated after

8 months of operation. During the 8-month evaluation period, the system was unable to prevent severe storm-induced erosion of the beach. However, the system did function to accrete beach material even under less-than-ideal soil conditions.

Shoreline response to mechanical beach dewatering at the Hirtshals sites was deemed encouraging and prompted the first full-scale demonstration of beach dewatering technology as a shoreline stabilization method. DGI installed a 500-m-long, 0.2-m-diam perforated drain pipe at Torsminde on the west coast of Denmark in 1985 (Vesterby 1991, Ovesen and Schuldt 1992). The drain pipe was buried at an elevation between -2.0 m and -2.5 m in a shore-parallel orientation in a beach composed of gravel and well-sorted, medium-grained sand superimposed on a layer of fine-grained lagoonal deposits occurring below -3.5 to -5.0 m. The Torsminde system operated until 1991, when the demonstration was intentionally terminated. Monitoring of the demonstration by DGI revealed that after 7 years of operation, the dewatered beach accreted approximately 30 m^3/m of beach material, while neighboring control beaches experienced approximately 25 m^3/m of erosion. Monitoring of the system also revealed that the drain had an effective length 100 m to 200 m longer than the actual drain pipe, and that no negative environmental effects were observed.

The performance of the beach dewatering systems designed by DGI led to commercial interest in the technology as a shoreline stabilization method. DGI is presently holder of U.S. patents covering beach-face dewatering technology and actively commercializing the technology as the Beach Management System™. In the United States, the Beach Management System is marketed under a patent license by CSI using the product name STABEACH™.

In 1988, under patent license to DGI, CSI installed a 580-ft-long STABEACH™ system at Sailfish Point (Stuart) on the Atlantic coast of Florida in a shore-parallel orientation (Terchurnian 1989, 1990; Ovesen and Schuldt 1992; Schuldt 1992b; Lenz 1994). The system was installed in a beach composed of medium-grained sand and initially yielded approximately 75 liters/second (ℓ/s) of discharge. The system was comprised of a 0.46-m-diam collector header with 1.2-m-long horizontal well points attached on 3.1-m centers. Following 11 months of operation, Dean (1990) concluded in an independent evaluation that it was not possible to differentiate between system-induced and naturally occurring morphologic changes, and that there were no adverse effects of the system on the beach. Subsequent monitoring of the Sailfish Point installation led Dean to conclude that the STABEACH™ System had a positive effect on the shoreline. Dean observed that the system induced moderate accretion on the dewatered shoreline, while adjacent non-dewatered beaches experienced erosion, and the dewatered beach was considerably more stable than adjacent non-dewatered beaches. Again, Dean observed no adverse effects on beach dynamics within the system's influence.

In 1993, CSI installed a second beach dewatering system at Englewood Beach located on the Gulf Coast of Florida (Lenz 1994). The system consisted of a series of well points along a 600-ft reach of shoreline. Following a limited

operational period, the system was rendered inoperable by a series of storm events, and not replaced.

In 1994, newly constructed European commercial beach dewatering installations included a 600-m-long Beach Management System installed by DGI at Enoe Strand on the south coast of Denmark, and a 180-m-long Beach Management System at Towan Bay, Cornwall, UK. The Towan Bay system was constructed by MMG Beach Management Systems, UK, Ltd., under patent license to DGI (Dredging and Port Construction 1994, 1995; Burstow 1995). In an early evaluation, Burstow (1995) reported a general accretionary trend of beach material on the foreshore at Towan Bay. To date, it is too early to draw definitive conclusions regarding system performance at the most recent European installations.

Researchers have experimented with gravity discharge methods, in addition to mechanized methods. In 1992, a field experiment was conducted at Dee Why Beach, Sydney, Australia, in which a nonmechanized beach dewatering concept was evaluated (Davis et al. 1992). A series of seaward-sloping coastal drains were installed in a shore-normal orientation below the beach in the swash zone. The system consisted of eighteen 0.9-m-wide and 25-m-long strip drains spaced at 5- to 15-m intervals, spanning 160 m of shoreline. Following 18 months of evaluation, Davis et al. concluded that the drains functioned to lower the near-coast groundwater elevation by 0.3 m at the location of the system and that the dewatered shoreline exhibited greater stability than pre-project conditions. Katoh and Yanagishima (1997) are presently monitoring a nonmechanized beach dewatering project located on the open coast at the Hazaki Oceanographical Research Station (HORS), Japan. The installation at HORS consists of a series of permeable drains covering a subsurface area extending 88 m in the cross-shore direction and 7.8 m in the alongshore direction. Each drain unit is 2 m in length, 1 m in width, and 20 cm in height, and is coupled in the longitudinal direction. The nonmechanized drainage system empties into a collection pipe and is discharged offshore by gravity. Katoh and Yanagishima conclude that the permeable layer installed below the active beach profile envelope functions to gravitationally drain groundwater to the offshore, reduce the rate of erosion during a storm event, and enhance the rate of post-storm recovery of the foreshore profile. Additionally, Katoh and Yanagishima observed that the drain system's influence extended beyond the physical location of the permeable layer.

CPAR Project Location

Nantucket Island is the easternmost member of the Elizabethan Island chain located 48 km southeast of the New England coast (Figure 1). The eastern shoreline of the island is exposed to direct attack from the high-energy wave environment of the North Atlantic. Mean offshore significant wave heights are on the order of 2 m. However, offshore significant wave heights in excess of 5 m are frequently measured, particularly during winter storms. The maximum wave height offshore measured between 1984 and 1993 was 11.6 m (Hubertz

1995). Historical charts and aerial photography indicate that, for at least the past 150 years, the beach face, dune line, and bluff face have experienced episodic accretion and recession (Tiffney, Weisha, and Andrews 1991). Present estimated erosion rates along the eastern shoreline range from 0.79 m/year to 7.6 m/year, depending on location. An analysis of wave refraction patterns suggested that episodic erosion events are due primarily to the focusing of storm wave energy on specific regions of the shore by an offshore shoal complex along the southeastern shoreline of Nantucket (Weishar et al. 1991).

Bluff and dune recession are presently encroaching on private and public facilities of several Nantucket coastal communities. On the eastern shore of the island, where coastal storm damage has been catastrophic, three STABEACH™ systems were installed to locally halt or retard shoreline recession (Figure 2). In the original plan, four systems were to be deployed along the shoreline. However, the local permitting agency requested that only two be initially deployed until the results of quarterly monitoring of their effect on the local groundwater, discharge water quality, and local ecology indicated no adverse impacts. The design of one of the approved systems was changed during construction due to a clay outcrop on the beach in which it was very difficult to install a drain. Therefore, the one system was separated into two individually functioning systems. The clay outcrop separates the systems. Hence, three individually operating systems were actually constructed on the Nantucket shoreline.

2 STABEACH™ Design

General System Design Concepts

According to Schuldt (1992a), the design of a beach dewatering system is a function of several fundamental elements. These elements include hydraulic conductivity of the subsurface beach, horizontal and vertical location of drain sections relative to the swash zone, and the presence of confining or impermeable subsurface layers. The system receives water from both the offshore and landward directions. However, when the drain lines are located below the active swash zone region of the beach profile, it is assumed that the amount of water received from the landward direction is negligible. Thus the offshore inflow may be approximated per linear meter of drain as follows:

$$q = \frac{k}{2L}(T_1^2 - T_2^2) \tag{1}$$

where

q = inflow rate (m^3/sec/m)

k = mean hydraulic conductivity of subsurface deposits (m/sec)

L = horizontal distance from the profile outcrop at the air/sea interface to the drain

T_1 = saturated thickness of the aquifer (m)

T_2 = vertical distance from the drain to top of impermeable subsurface layers

The region near the seaward boundary of the beach profile is dynamic. Equation 1 is an approximation of inflow. Inflow will vary with changing water elevations at the seaward boundary of the profile, changing values of the horizontal distance from the drain to the seaward boundary with erosion and accretion of beach material, and variation in local aquifer elevations.

Hydraulic conductivity or permeability coefficient values (*k*) for the project site at Nantucket were calculated based on grain size analyses of subsurface soil samples. Mean values of *k* were used for the dimensioning and design of drains, collector pipes, discharge pipes, and pumps installed at each location.

Each of the three STABEACH™ systems installed at Nantucket is comprised of three basic components: drain and conduit sections; a collector well/pump station; and a discharge line. Based on data obtained from geotechnical borings and preliminary pump evaluations, systems were designed to yield a calculated discharge as a function of drain capacity and pumping rate. Drain sections are comprised of 0.31-m-diam polyethylene (PE) perforated (0.5 mm) corrugated pipe wrapped with a geotextile filter material to prevent soil from entering the drain and collector well. These sections are also referred to as the screened sections. The sections are installed below the swash zone region of the profile at about -2.1 m MLW. Burial depth of system components is based on previous experience by the contractor. The depth provides sufficient buffer in the sand cover for protection during erosive periods and sufficient depth for a cone of depression to form in the groundwater table over the drain. The screened sections are attached to 0.31-m-diam PE conduits, which empty into collector wells located at the landward extent of the beach profile. Collector wells are 1.2 m in diameter and about 9 m deep. Wells are installed vertically with the top of a well located at the local beach elevation (Figure 3). Water drains to the collector wells, where it is then discharged offshore by pumps through 0.46-m-diam PE pipes extending offshore from the collector wells.

Two methods of construction were used to install STABEACH™ drain sections. A trenching machine was used to automatically install the drain sections and conduits below the beach face. This method of installation was used to minimize the need for excavation and temporary dewatering. The trenching method is limited by the diameter of pipe (0.31 m maximum diameter) that may be installed. Therefore, parallel drain sections were installed at Lighthouse South and North to increase the volume capacity and longshore extent of influence (Lenz 1994). When necessary, excavation with a backhoe was used to install drain sections. For example, material with low permeability (clays in particular) was excavated and backfilled with more permeable material over drain sections at the Lighthouse South and North systems.

System design assumed that the pipes would be buried using trenchless technology, which allows a maximum of 0.31-m-diam pipe. Since a single 0.31-m-diam pipe has a given carrying capacity over a given length of beach, several pipes were sometimes required to achieve the desired design discharge. For example, if the drain lines were required to extend 310 m north of a wetwell, two pipes might be used (each with a 155-m screened section). One pipe would be 155 m long extending outward from the wetwell. The second pipe would be 310 m long, where only the last 155 m of the pipe was perforated. In this way, the desired 310 m of beach would be covered by screened drain pipe. Decisions regarding the number of drain lines to install and length of perforation in each line were made by CSI.

Soil Conditions

A pre-project geological and hydrological site characterization was conducted by CSI at proposed STABEACH™ locations (Coastal Stabilization, Inc. 1994). The objective of the site characterization was to evaluate the subsurface conditions of the beach to optimize design for effective operation of the STABEACH™ systems. Surfacial geologic features at Nantucket control the subsurface hydrology. Surfacial features were formed primarily during the period of Wisconsinian glaciation and are superimposed on underlying marine deposits. The shoreline in the vicinity of Sankaty Head Light and Siasconset is composed largely of ice-contact deposits, glacial till, gravel, sand, and silt (Oldale 1985, 1987). Therefore, samples were collected at varying depths below the beach surface to estimate hydraulic conductivity of the beach subsurface, and to determine the presence of clay or silt layers that may inhibit the flow of groundwater to the drain sections. Sample elevations ranged between 0 and -9 m MLW. Pump tests were conducted at observation wells to confirm hydraulic conductivity estimates and to aid in the optimal drain-system designs.

Subsurface borings

Four borings were completed along 380 m of beach at Codfish Park to the -9-m MLW depth between profile markers 84 and 86 (Figure 2). Analysis of the borings reveals that the Codfish Park beach subsurface is characterized by clean (i.e., no fines), uniform, medium to coarse sands superimposed on a cobble layer located at approximately -8.2 m MLW. Thirteen borings were completed along 945 m of beach located between profile markers 90 and 94 (Figure 2). The region of shoreline located between profile markers 90 and 94 below Sankaty Head Light is characterized by a sandy beach fronting a 27-m-high coastal bluff. The region is divided into south (Lighthouse South), middle, and north (Lighthouse North) sections for discussion. The subsurface of the Lighthouse South section, extending 128 m from north of profile marker 90 for approximately 404 m is characterized by clean, fine to coarse sands. The Lighthouse South and North sections are separated by a reach of beach dominated by a large clay outcrop on the bluff and boulders at the beach face. Borings completed at the middle section reveal a dipping subsurface silt/clay layer rising to an elevation of -2.7 m MLW below silty sands. The Lighthouse North section is a 180-m reach of beach that extends south from 31 m to the north of Sankaty Head Light. The subsurface of the Lighthouse North section is comprised of medium sand with limited amounts of silt and clay. Silt and clay layers were identified between about -4 m and -5 m MLW.

Soil hydraulic conductivity

Hydraulic conductivity values were calculated for proposed beach dewatering system locations at Codfish Park (CFP), Lighthouse South (LHS), and Lighthouse North (LHN) based on analysis of soil samples obtained from

subsurface borings. Hydraulic conductivity values calculated by CSI are presented in Table 1 for each system location.

Table 1
Calculated Soil Hydraulic Conductivity Values

Location	Minimum (μm/sec)	Maximum (μm/sec)	Mean (μm/sec)	Mean[1] (mm/sec)
CFP	600	4400	1730	2330
LHN	300	1700	770	890
LHS	100	300	200	

[1] Mean above -3.1 m MLW.

Codfish Park STABEACH™ Parameters

The system installed at Codfish Park was originally intended to yield approximately 190 ℓ/s, over all phases of the tide. However, following construction, the capacity of the system was nearly twice the value expected. As constructed, the Codfish Park system is 368 m in length, and is comprised of three drain sections. Referring to Figure 4, the south drain section is 170 m in total length, including 122 m of screened perforated line. The north drain section is 198 m in total length, including 183 m of screened perforated line. Both sections empty to a single collector well. Drain sections were installed at the -2.1-m MLW elevation at the furthest extent from the collector well, and rise to the -0.6-m MLW elevation at the well. A 0.31-m screened drain line was installed directly seaward of the collector well to augment beach drainage in the vicinity of the unscreened northern and southern sections. The 0.31-m supplemental drain also empties directly to the well. Drained water is discharged offshore from the well through a 64-m-long, 0.46-m-diam line.

Due to the slope of the primary drain sections, drainage at the Codfish Park system is aided by a low-volume vacuum pump. The 3-hp pump was designed to operate with approximately 0.10 m of Hg of vacuum on the collector well. Under 0.10 m of vacuum and a single 25-hp discharge pump operating at capacity, the system yields 192 ℓ/s of flow. The total operating capacity of the system is designed to yield 315 ℓ/s to 375 ℓ/s, but is limited by discharge pump capacity. Flow measurements from a sampling period in March 1995 and drain lengths are summarized in Table 2 for each section draining independently and for all lines draining concurrently.

During a second observational period in September 1996, flow measurements were made on the system, with and without operation of the vacuum pump. These observations are summarized in Table 3.

Table 2 Codfish Park Drain Flow Measurements (March 18, 1995)				
Section	**South**	**Supplement**	**North**	**System Total**
Length (m) Total Screen	 170 122	 30	 198 183	 368 335
Independent Draining (High Tide)				
Q_{max} (l/s)	170	16	190	375
Q_{max}/m[1] Total Screen	 0.99 1.39	 0.52 0.52	 0.95 1.03	 0.94 1.12
Concurrent Draining (High Tide)[2]				
Q (l/s)	86 (Estimated)	13 (Estimated)	94 (Estimated)	192 (Measured)
Q/m[1] Total Screen	 0.50 0.70	 0.41 0.41	 0.47 0.51	 0.48 0.57
Independent Draining (Low Tide)				
Q_{max} (l/s)	145	13	158	315
Q_{max}/m[1] Total Screen	 0.85 1.19	 0.41 0.41	 0.80 0.86	 0.79 0.94
Concurrent Draining (Low Tide)[2]				
Q (l/s)	86 (Estimated)	13 (Estimated)	94 (Estimated)	192 (Measured)
Q/m[1] Total Screen	 0.50 0.70	 0.41 0.41	 0.47 0.51	 0.48 0.57

[1] Flow per linear meter calculation based on total section length and screen length.
[2] Flow measured with all pumps pumping at capacity and 0.10 m of Hg of vacuum on the collector well.

Lighthouse South STABEACH™ parameters

The system installed at Lighthouse South was designed to yield approximately 380 ℓ/s over all phases of the tide. As constructed, the Lighthouse South system is 558 m in length, and is comprised of six drain sections. Referring to Figure 5, three drain sections extend to the south. Two sections (S1 and S2) extend approximately 310 and 244 m from the collector well location and consist of 60 m (S1) and 80 m (S2) of perforated screened lines. The remaining section, S3, extending to the south is 163 m in length, with 133 m of perforated screened line. Two drain sections extend to the north at Lighthouse South. The first drain section, N1, extends 253 m and has 100 m of screened

Table 3 Codfish Park Drain Flow Measurements (September 1996)		
High Tide		
Q (l/s)	161	0.13 m of Hg vacuum
Q/m[1] Total Screen	 0.40 0.48	0.13 m of Hg vacuum
Q (l/s)	114	No vacuum
Q/m[1] Total Screen	 0.28 0.34	No vacuum
Low Tide		
Q (l/s)	169	0.13 m of Hg vacuum
Q/m[1] Total Screen	 0.42 0.50	0.13 m of Hg vacuum
Q (l/s)	435	No vacuum
Q/m[1] Total Screen	 0.23 0.27	No vacuum

[1] Flow per linear meter calculations based on total section length and length of screen.

perforated line at the northern extent. The second section, N2, is approximately 165 m in length, with 116 m of screened perforated line. Similar to the Codfish Park system, a 24-m screened perforated section of drain was installed fronting the collector well area to augment beach drainage in the vicinity of unscreened portions of the south and north sections. Drain sections were installed at the -2.1-m MLW elevation. All three functioning sections empty to two collector wells located at the backshore region of the beach profile. Water is discharged offshore from the wells through a 53-m-long, 0.46-m-diam line.

Due to the presence of sand in the drain sections following construction, sections S1, S2, and N1 were not used. The exact cause for the presence of sand in the drain sections has not been determined. However, it is speculated that either the geosynthetic filter fabric covering the perforated drain line, or the unperforated drain line was damaged during construction. The induction of sand to the discharge pump could render the pump inoperable. CSI decided to abandon the damaged drain sections and operate with the two functional sections.

The Lighthouse South system operates under gravity drainage. Discharge of drained water from the collector wells is by a single 25-hp pump. With the two functional drain sections, the capacity of the Lighthouse South system varies between 246 ℓ/s and 277 ℓ/s. System drain lengths and flow measurements from

a sampling period in March 1995 are summarized in Table 4 for each line draining independently and for all lines draining concurrently.

Table 4
Lighthouse South Drain Flow Measurements (March 17, 1995)

Drain Section	South	Supplement	North	System Total
Length (m) Total Screened	 163 133	 24	 165 116	 352 273
Independent Draining (High Tide)				
Q_{max} (ℓ/s)	107	88	121	317
Q_{max}/m[1] Total Screened	 0.66 0.81	 3.62 3.62	 0.74 1.05	 0.90 1.16
Concurrent Draining (High Tide)				
Q (ℓ/s)	95 (Estimated)	78 (Estimated)	106 (Estimated)	277 (271-284) (Measured)
*Q/m Total Screened	 0.58 0.71	 3.18 3.18	 0.64 0.91	 0.79 1.02
Independent Draining (Low Tide)				
Q_{max} (l/s)	91	69	104	265
Q_{max}/m[1] Total Screened	 0.56 0.69	 2.84 2.84	 1.05 0.90	 0.75 0.97
Concurrent Draining (Low Tide)				
Q (l/s)	85 (Estimated)	64 (Estimated)	96 (Estimated)	246 (240-252) (Measured)
Q/m[1] Total Screened	 0.52 0.64	 2.64 2.64	 0.59 0.83	 0.70 0.90

[1] Flow per linear meter calculations based on total section length and length of screen.

Lighthouse North STABEACH™ parameters

The Lighthouse North system was designed to yield 380 ℓ/s over all phases of the tide at pump capacity. As constructed, the Lighthouse North system is 418 m in length, and is comprised of four drain sections. Referring to Figure 6, two drain sections extend from the collector well to the south. Section S1 is 265 m in total length with 128 m of screened perforated line. Section S2 is 158 m in total length with 100 m of screened perforated line. The section extending to the north is 152 m in total length with 122 m of screened perforated line. A 24-m screened perforated section of drain was installed fronting the collector well area

to augment beach drainage in the vicinity of unscreened portions of the south and north sections. Drain sections were installed at the -2.1-m MLW elevation. All four functioning sections empty to two collector wells located at the backshore region of the beach profile. Water is discharged offshore from the wells through a 53-m-long, 0.46-m-diam line.

The Lighthouse North system operates under gravity drainage. Drained water is discharged from the collector wells by a single 25-hp pump. The capacity of the Lighthouse North system, as constructed, varies between 183 and 195 ℓ/s. System drain lengths and flow measurements from a sampling period in February 1995 are summarized in Table 5 for each line draining independently and for all lines draining concurrently.

Table 5
Lighthouse North Drain Flow Measurements (February 26, 1995)

Drain Section	South S1	South S2	Supplement	North	System Total
Length (m) Total Screened	 265 128	 160 100	 24	 152 122	 600 372
Independent Draining (High Tide)					
Q_{max} (l/s)	64	56	22	82	225
Q_{max}/m[1] Total Screened	 0.24 0.50	 0.35 0.58	 0.91 0.91	 0.54 0.67	 0.37 0.60
Concurrent Draining (High Tide)					
Q (l/s)	56 (Estimated)	49 (Estimated)	19 (Estimated)	72 (Estimated)	196 (Measured)
Q/m[1] Total Screened	 0.21 0.44	 0.31 0.50	 0.78 0.78	 0.47 0.60	 0.33 0.53
Concurrent Draining (Low Tide)					
Q_{max} (l/s)	52 (Estimated)	46 (Estimated)	18 (Estimated)	67 (Estimated)	183 (Estimated)
*Q_{max}/m Total Screened	 0.21 0.41	 0.29 0.47	 0.74 0.74	 0.44 0.55	 0.30 0.49

No data available for independent pump tests at low tide.
[1] Flow per linear meter calculations based on total section length and length of screen.

3 STABEACH™ Operation

All three STABEACH™ Systems located at Nantucket were started on November 22, 1994. The percent of time each system operated during a given quarter of the monitoring program is summarized in Table 6. The operation time of the systems was monitored by onsite SBPF and CSI personnel. The systems were intended to operate continuously, but due to power failures, difficulties reestablishing power, and some equipment failures, the systems were operated more intermittently. The operational period of each dewatering system is summarized in Table 6.

Table 6
Nantucket STABEACH™ System Operation

Monitoring Period	Codfish Park (%)	Lighthouse South (%)	Lighthouse North (%)
Nov 94-Mar 95	56	27	69
Mar 95-May 95	95	94	95
May 95-Sep 95	95	73	95
Sep 95-Dec 95	95	95	95
Dec 95-Feb 96	39	24	95
Feb 96-Jun 96	50	0	95
Jun 96-Sep 96	65	42	95
Sep 96-Dec 96	62	95	95
Dec 96-Feb 97	95	95	95

Field Monitoring Program

The field monitoring program was established to quantify the performance of the dewatering systems relative to untreated (control) beaches. Based on the review of previous lab and field experiments and other full-scale dewatering system deployments, it was expected that the dewatering systems would build

higher, wider beaches in the vicinity of the drain lines with a steeper foreshore slope. There was little certainty about how quickly accretion would occur in the presence of a dewatering system, but it was speculated that the dewatering systems would accelerate accretion during generally accretionary times along the shore in a quantity sufficient to offset erosive losses during generally erosive periods. Consequently, it was expected that long-term shoreline stability would be observed in the vicinity of the dewatering systems, but that short-term fluctuations in shoreline position might be observed. Therefore, the monitoring was designed to capture short-term (3 months or less) and long-term (years) evolution of the shoreline.

The field monitoring program included onshore beach-profile measurements taken quarterly that extended from the back of the beach to approximately the -1-m MLW contour (wading depth). The eastern shoreline of Nantucket had a historic set of profile lines already established prior to the initiation of the present monitoring program. The historic profile lines were approximately 300 m apart and provided sufficient coverage of the study region. Therefore, they were selected for continued monitoring. Additional profile lines were established between the historic ones. At the start of the monitoring program, it was uncertain whether other dewatering systems would be installed during the program. Therefore, the beach profile lines that were established were expected to capture data in the areas where additional systems might be installed, as well as control beaches. The established onshore beach profile lines were then extended offshore via fathometer surveys to the -6.1-m contour. The offshore profiles were measured twice a year.

Aerial photographs were taken quarterly to capture changes in the planform view of the shoreline in the vicinity of the drains, especially changes that might occur between profile lines. While the profile measurements would probably be sufficient to show any significant changes in the shoreline, it was not certain. The aerial photographic images would provide a continuous planform view of the shoreline to support or add to conclusions that were drawn from measurement and analysis of the beach profiles. Also, in the event that the dewatering systems induced an obvious change in the planform view of the shoreline, capturing it in a photograph would help in marketing the technology in the future.

Digital-image monitoring of the shoreline along the Sankaty Head Lighthouse was used to observe the shoreline between quarterly profile measurements. Changes in the beach and nearshore morphology were recorded on an hourly basis. The dynamic nature of the eastern Nantucket shoreline was unknown, but it was expected that frequent snapshots of the shoreline would capture changes that might be missed by the quarterly monitoring.

The wave climate for the eastern shoreline of Nantucket was analyzed based on hindcast waves to determine the potential accretion and erosion trends. While the analyzed waves were hindcast for the period 1956-1975, they provide a good indication of the general wave climate for Nantucket.

Groundwater elevation in the vicinity of the dewatering systems was measured to verify that the systems were inducing a drawdown in the beach groundwater table and to determine the influence of the drawdown on the local freshwater aquifer.

The environmental influence of the dewatering systems was monitored by evaluating vegetation and meiofaunal communities of the beach in the vicinity of the systems. The monitoring was intended to verify that the drawdown of the water table in the beach did not adversely impact these communities. Also, the water quality of the discharge from the systems to the ocean was monitored to be sure that discharges did not contain levels of bacteria and nitrates significantly higher than background ocean water quality levels.

Beach Profile Data Collection Methods and Analysis

In November 1994 (pre-construction), 42 beach profile monitoring transects were established and surveyed on a quarterly basis through February 1997 (Figure 2). The survey area extended 10 km along the shore with survey transect 81 at the south end and transect W at the north end. Profile transects were regularly spaced at approximately 310-m intervals, with the exception of 123-m intervals in the vicinity of existing system drain pipes and proposed locations for future drain installations. For reference, the Codfish Park system extends from 67 m south of transect 86 to 44 m north of transect 84; the Lighthouse South system extends from 163 m south of transect 91 to 165 m north of transect 91; the Lighthouse North system extends from 46 m north of transect 92 to 123 m north of transect 93.

Each transect extended from the crest of the dune or base of the coastal bank to wading depth (-1 m MLW) and was surveyed with a total station and prism rod system. Elevations were surveyed at 6.1-m intervals from the baseline to wading depth and at inflection points in the profile slope. All surveys were conducted by Blackwell and Associates, Inc., Nantucket, MA, to ensure consistency of survey methods.

The 42 onshore transects established for beach profiles were extended offshore to the -6.1-m contour using a ship-mounted digital fathometer interfaced to the Coastal Oceanographics, Inc., computer operating the HYPAC™ program. Hydrographic surveys were conducted in November 1994, December 1995, and September 1996 using standard fathometer techniques. All fathometer surveys were conducted with the same equipment and boat by Coastal Planning and Engineering, Inc., Boca Raton, FL, to ensure consistency of survey methods. In September 1995 and June 1996, Scanning Hydrographic Operational Airborne Lidar System (SHOALS) surveys were conducted (Lillycrop, Parson, and Irish 1996). Complete SHOALS surveys of the Lighthouse North and Lighthouse South offshore regions were obtained on both occasions, while surveys offshore of Codfish Park were unobtainable due to water clarity, weather, and logistical

limitations. Periods for the onshore and offshore measurements are summarized in Table 7.

Table 7
Summary of Surveys

Date	Onshore	Offshore - Method
7-19 Nov 1994	X	X - fathometer
28 Feb - 7 Mar 1995	X	
30 May - 01 Jun 1995	X	
25 Sep - 2 Oct 1995	X	X - SHOALS
9-18 Dec 1995	X	X - fathometer
27 Feb - 1 Mar 1996	X	
5-8 Jun 1996	X	X - SHOALS
24-30 Sep 1996	X	X - fathometer
11-13 Dec 1996	X	X - fathometer
24-28 Feb 1997	X	

Quarterly beach profile data were analyzed for volume and shoreline change. Quarterly measurements document seasonal variability, and comparisons to the preconstruction surveys document the longer-term trends. The November 1994, December 1995, and September 1996 surveys for profiles 86 and 97.3 are shown in Figure 7. Reasonable profile closure occurs at around -6.1 m MLW on profile 97.3. Nevertheless, profile 86 shows significant vertical changes over the same time period. This closure problem is indicative of the closure for the southern profiles. Because the southern profiles do not close, estimation of profile volume changes in this area may not be accurate.

The lack of closure of the southern offshore beach profiles is believed to be the result of a dynamic surf zone whose coastal processes are complex. The complexity is due to wave refraction and diffraction over a spatially variable bathymetry. Near Codfish Park, a large shoal that extends to the southeast significantly affects the wave climate. This shoal has been previously studied and found to be dynamic (Tiffney, Weishar, and Andrews 1991; Weishar et al. 1991). In addition to the complex wave climate, longshore tidal currents affect the nearshore hydrodynamics. These currents are bidirectional (with the tide) and may reach 0.82 m/s and 0.98 m/s at maximum ebb and flood conditions, respectively (NOAA 1993). Sediment transport may be occurring that might not otherwise occur without the presence of the currents. Due to the lack of profile closure, only the data above and including the -1-m MLW elevation were used in the volumetric analysis of the data.

The change in shoreline position measured at the 0.0-MLW contour between November 1994 and February 1997 is provided in Table 8. Negative values indicate erosion of the shoreline. The change in beach volume measured to the -1-m contour is also provided in Table 8.

Table 8
Average Shoreline Change and Volume Change Over Selected Reaches of Shoreline

Reach Segment	Shoreline Change (m)	Volume Change (m^3/m)
South of Codfish Park (Profiles 81-84)	-18.2	-96
Codfish Park (Profiles 84-86)	-6.7	-38
Between Codfish Park & Lighthouse South Systems (Profiles 86-90.6)	-9.6	-40
Lighthouse South (Profiles 90.6-91.5)	-6.7	-31
Between Lighthouse South and North Systems (Profiles 91.5-92)	-5.4	-19
Lighthouse North (Profile 92-93.5)	-2.7	-5
North End of Project (Profiles 93.5-96.5)	-5.1	-20
North of Project Area (Profiles 96.5-99)	-0.9	-8

Besides computating long-term trends in accretion and erosion, such as those provided in the table, each quarter's profile measurements were compared to the previous quarter to give some indication of short-term trends. The primary method of analysis of the short-term trends made use of an even-odd technique to withdraw information from the shoreline and volume change data. The results of the analyses were correlated with the operational status of the systems over the given period. In addition, the impact of longshore dispersion of sand, the probability of cross-shore sediment transport, the standard deviation of the project's contours, the evolution of the project's berm heights, and beach slopes were studied.

Even-odd analysis: Summary

Any continuous mathematical function about an origin can be broken down into an even function for those characteristics symmetric about the origin and an odd function for those characteristics that are nonsymmetric about the origin. This mathematical technique has been used in the analysis of inlets on shorelines (Work and Dean 1990) and in the analysis of a breakwater on a shoreline (Dean and Pope 1987). The theory as applied to the Nantucket shoreline assumed that cross-shore sediment transport processes would be captured by the even function while longshore sediment transport processes would be captured by the odd function. It is important to note that the theory is only a mathematical analysis

method and is not based on the physics of the problem. The results need to be interpreted carefully and it should be noted that more than one interpretation of the results is possible. The following is a summary of the even-odd analysis conducted by Coastal Planning & Engineering, Inc. The full analysis is provided in Appendix A.

In the even-odd analysis of the Nantucket data, one major trend relevant to the impact of the dewatering systems on shoreline response is apparent. The dewatering systems appear to be more effective when they operate near their capacity. This trend is relevant to the analysis because only one of the three dewatering systems operated near full capacity for the entire study period. If the dewatering systems are not functioning, they cannot be expected to influence processes controlling the cross-shore transport of sediment on the foreshore.

In the analysis, the Lighthouse South and North systems were considered as one system because of their proximity to one another. Dewatered beach responses are summarized in Table 9 for the duration of the monitoring period. This should be related to Table 6, which provides the percent of time the systems were operating during a given quarter. (For convenience, Table 9 notes those quarters in which the systems operated more than 70 percent of the time.) When the Codfish system operates at a rate over 70 percent, the even functions show a relative increase in beach width within the dewatering system compared to areas outside of the system in 67 percent of the monitoring periods. When the Codfish system operates under 70-percent capacity, the even functions only show a relative increase in 40 percent of the study periods. When Lighthouse South operates more than 70 percent of the time, the even functions show a relative increase in beach width within the dewatering system compared to areas outside the dewatering system (60 percent of the time). When Lighthouse South operated less than 70 percent of the time, the even functions showed a relative increase only 50 percent of the time.

Table 9
Summary of Shoreline Response

Monitoring Period	Codfish Park Even Function	Codfish Park Odd Function	Lighthouse Even Function	Lighthouse Odd Function
Nov 94-Mar 95	Reduced erosion	Southerly drift	Reduced erosion	Northerly drift
Mar 95-May 95	Enhanced erosion[1]	Southerly drift	Accretion[1]	Northerly drift
May 95-Sep 95	Accretion[1]	Southerly drift	Reduced erosion[1]	Northerly drift
Sep 95-Dec 95	Reduced erosion[1]	Southerly drift	Enhanced erosion[1]	Uncertain
Dec 95-Feb 96	Enhanced erosion	Northerly drift	Reduced erosion	Uncertain
Feb 96-Jun 96	Enhanced erosion	Uncertain	Enhanced erosion	Southerly
Jun 96-Sep 96	Enhanced erosion	Northerly drift	Enhanced erosion	Uncertain
Sep 96-Dec 96	Accretion	Uncertain	Reduced erosion[1]	Uncertain
Dec 96-Feb 97	Accretion[1]	Uncertain	Enhanced erosion[1]	Uncertain

[1] System operated more than 70 percent of the time.

The gap between these two statistics widens if the first monitoring period is ignored. During the first period of study, the dewatering systems were being installed. Therefore, none of the systems operated at peak capacity when the period as a whole is analyzed. For example, the Lighthouse North system had an overall capacity of 69 percent for the quarter, despite operating at a 95-percent rate (95 percent is full capacity) after completing installation on December 20, 1994. Because the date of the initial survey does not coincide with the beginning of full operation by the systems, the first quarter may not be relevant in this type of analysis. If the first quarter is ignored, the even functions show relative increases in beach width within the Codfish dewatering systems during 75 percent of the monitoring periods in which the pumps operated over 70 percent of the time. However, when the Codfish pumps operated less than 70 percent of the time, only 25 percent of the periods (not including the first quarter) showed a relative even function increase within the system areas. At the Lighthouse system, operating the south system at greater than 70 percent of the time yields increasing even functions 60 percent of the time. If the south system is not operated 70 percent of the time, an even function increase occurs only 33 percent of the time.

Shoreline behavior exhibited within the dewatering systems can possibly be explained by making use of the even-odd models presented in Appendix A. The majority of periods in which the systems operate at over 70 percent of the time exhibit an even pattern similar to the nourishment model. One explanation of this behavior is that when operating near full capacity, the systems reduce the erosion within their limits by decreasing the amount of offshore sediment transport (or increasing the amount of onshore transport). This is similar to a nourishment in that a beach nourishment can be thought of as a large singular increase in the onshore sediment transport. However, when the system operates for less than 70 percent of the time, the majority of the quarterly analyses exhibit an even function whose pattern is similar to the protruding shoreline model, or to the opposite of the nourishment model.

This type of behavior can be explained by the perturbation in the shoreline created by a higher rate of erosion in the previous operating system due to diffusion. In addition, the perturbation could be losing sediment offshore as the beach profile returns to its equilibrium position. The patterns, which are similar to the opposite of the nourishment example, could be representative of offshore transport while the "W-" shaped protruding shoreline patterns could indicate diffusion losses. In summary, when operated near their capacity, the systems seem to decrease the erosion within their limits. However, when the systems are operated at less than their capacity, erosion within the system limits seems to increase. The increase is most likely due to diffusion or cross-shore equilibration.

All reversals in the direction of longshore sediment transport directions for Codfish Park and all of the net southerly transport for the project area are grouped closely in terms of time. Therefore, it is likely that natural forces were responsible for the changes in direction, rather than the influence of the dewatering systems.

Based on the limited even-odd function analyses, the following processes may have occurred at the dewatering system locations:

a. Relative shoreline advancement within the limits of the dewatering system when the system was operated near capacity.

b. Accumulated sand lost over the dewatering system when the system was not operating at capacity.

Beach profile stability

If the dewatering technology stabilizes the beach or enhances the recovery after storms, the shoreline could be expected to experience less erosion and/or more accretion than adjacent non-dewatered shorelines. A useful measure of shoreline stability may be the standard deviation of shoreline position where the standard deviation of a dewatered shoreline about a mean position should be less than that of a non-dewatered shoreline. This approach to assessing a dewatered shoreline is speculative. It may be that during the initial stages of dewatering, the standard deviation would be greater as the system may induce larger changes in the beach profile than occurs in adjacent beach profiles. Further, if a dewatering system is not operated continuously, fluctuation in shoreline position due to running the system for a time and then shutting the system down for a time may result in higher-than-normal standard deviation. The standard deviation of the MLW and -1.8-m MLW contour positions for each profile in the study area were calculated (Table 10).

Table 10
Beach Profile Variability

Study Area	MLW Average Standard Deviation (m)	+1.8-m MLW Average Standard Deviation (m)
Codfish Park	5.2	4.1
Lighthouse North and South	2.1	2.4
All non-dewatered profiles	3.3	3.4
6 profiles adjacent to Codfish Park	5.6	4.5
6 profiles adjacent to Lighthouse North	1.9	1.9
6 profiles adjacent to Lighthouse South	3.5	3.9

Table 10 indicates that the Lighthouse dewatering system profiles exhibit less fluctuations than all profiles outside the dewatering systems when compared to the MLW and 1.8-m MLW contours. When the Lighthouse dewatering profiles are compared to their adjacent profiles, the results are mixed. No reduction in the standard deviation of shoreline position occurred at the Lighthouse systems when compared to the profiles adjacent to Lighthouse North. The profiles adjacent to Lighthouse South showed greater fluctuations (less stability) than the profiles within the dewatering system.

The profiles at the Codfish Park dewatering system have a lower standard deviation in shoreline position when compared to adjacent profiles. However, the magnitude of the improvement is not great (5.2 m versus 5.6 m).

Another measure that could be indicative of a dewatering system's impact in shoreline stability is berm height change. The berm elevation of each profile was measured (from the survey data) at a point approximately 4.6 m seaward of the November 1994 dune position. This point was assumed to be representative of the berm. Elevations at these stations were tracked throughout the study period. Table 11 summarizes the results. The range in berm elevations was determined by subtracting the lowest berm elevation from the highest berm elevation for each profile. This is an indication of the berm elevation dynamics.

Table 11
Average Berm Elevation

Study Area	Elevation Change Nov 94 to Feb 97 (m)	Elevation Range (m)
Codfish Park	-0.6	1.4
Lighthouse North and South	-0.2	1.0
All non-dewatered profiles	-0.3	1.1
6 profiles adjacent to Codfish Park	-0.7	1.6
6 profiles adjacent to Lighthouse North	-0.4	1.0
6 profiles adjacent to Lighthouse South	-0.5	1.4

Table 11 indicates that the profiles within the Codfish Park system experienced slightly less berm elevation loss than untreated adjacent profiles, and the range of berm elevations was also slightly less. Nevertheless, the dewatering system was unable to stabilize the berm, as 0.64 m of sand was lost.

At the Lighthouse dewatering systems, the beach experienced less berm elevation loss and less elevation range than adjacent profiles, which may be viewed as a measure of success of this system. Nevertheless, the beach elevation lost 0.18 m within the bounds of the systems.

In theory, dewatering systems increase the stability of a shoreline by decreasing the net offshore sediment transport. In the absence of other forces, an increase of onshore transport, coupled with a decrease in offshore transport, will create a steeper beach slope. A steepening of the beach slope was observed in the laboratory and at another dewatering system installation site which was deemed successful (Dean 1990). A dewatering system that is affecting the shoreline positively might be expected to increase the beach slope within its reach's influence.

Beach profile slopes were determined for each profile as the linear slope from the +1.8-m MLW to -0.3-m MLW elevations. This analysis was performed for each study area during the time period when the system operated at its highest level. For Lighthouse South and Codfish Park, the highest operation level was

between March 1995 and December 1995. For Lighthouse North, the highest operation level was from November 1994 to February 1997. The slope results are presented in the form of the cotangent of the angle that the beach slope makes with the horizontal in Table 12.

Table 12
Beach Slope Variation

Study Area	Cotangent Slope (Initial)	Cotangent Slope (Final)
Lighthouse North	6.9	6.3
[1]Adjacent profiles	6.7	6.3
Lighthouse South	6.2	6.0
[1]Adjacent profiles	7.0	6.0
Codfish Park	7.6	6.4
[1]Adjacent profiles	8.8	7.9

[1] Six profiles immediately adjacent to system.

Lighthouse North profiles showed a mild steepening from cotangent values of 6.9 to 6.3, but the adjacent profiles showed similar trends. Lighthouse South profiles steepened from cotangent values of 6.2 to 6.0, but the adjacent profiles steepened more, from 7.0 to 6.0. At Codfish Park the profiles steepened from cotangent values of 7.6 to 6.4, but the adjacent profiles also steepened from 8.8 to 7.9. While the total steepening adjacent to Codfish Park is less than within the system's influence, the magnitude of the steepening is approximately the same.

Generally, beaches on Nantucket are steep compared to other beaches found in the United States having slope cotangents more typically around 10 - 30. The natural steepness at Nantucket is due to the wave climate and the coarse-grain quartz sediment (0.6 mm). While the dewatered beaches within the study areas steepened, the difference in steepening between dewatered and adjacent profiles is minimal. Steepening does not appear to have occurred as a result of dewatering.

Digital Image Monitoring

A video imaging system was installed at the eastern shore of Nantucket to monitor the effectiveness of the Lighthouse North STABEACH™ system. This system was used to record changes in shoreline position and to measure coastal bank erosion. Video monitoring started 21 September 1995 and continued through 11 April 1997. The advantage of this system is that the shoreline and nearshore regions can be monitored on an hourly basis and measurements can be made from the recorded images. The video system is not as accurate as traditional survey methods, but it does reveal rapid morphological changes, particularly during storm events, that might be missed by quarterly surveys.

Due to the convex orientation of the eastern Nantucket shoreline, it was difficult to find an elevated site that had an uninterrupted view of the beach. A suitable and secure location was Sankaty Head Light, which offered a view of the Lighthouse North dewatering system. Three video cameras were mounted under the lantern room deck (Figure 8) to provide views of the nondewatered beach to the north, and the dewatered shoreline to the east and south.

The system collected a single-frame video image, called a snapshot, and a time-averaged video image, called a time exposure. The time-exposure image clearly reveals the location of active wave breaking, which in turn indicates shallow water such as a sandbar or the shoreline. The images were created by averaging several images taken over a 10-min period. This smoothed out changes in wave-breaking locations and produced a statistically more significant image of the wave dissipation regions. The Nantucket shoreline near the lighthouse lacked significant sandbars, so the wave dissipation was primarily at the shoreline. An hourly snapshot and time exposure were taken from each camera during daylight hours (between 0600 and 1900 EST). Over 30,000 images were collected through the 19-month video monitoring period.

Selected images from each camera are shown in Figures 9, 10, and 11. The white marks in the images identified as "GCP" (ground-control points) are known locations. These points aid in taking measurements directly off the images. Although only two GCPs are required for a geometric solution, using additional points results in a more accurate estimate.

Shoreline positions were measured from the oblique video images with image rectification to get a map, or planform view, as shown in Figure 12. Similar rectifications were done with images from the east- and south-facing cameras. Comparisons of rectified images show no significant changes in shoreline position throughout the video monitoring period. As an example, shoreline positions measured from the east-facing camera between April 4, 1996 and April 11, 1997 are compared in Figure 13. Also, no significant short-term variations in the shoreline were evident over the monitoring period. This result further verifies the stability of the northern portion of the Nantucket shoreline.

Aerial Photography

Figures 14-16 provide aerial views of the regions of beach where the dewatering systems were installed. The 1997 aerial photographs are used as the backdrop in the figures. The beach wetline for 1997 is indicated on each photograph along with the top bank and toe of the bluff. The lines indicating the dewatering systems do not indicate their position on the beach; just the reach of beach covered by the systems. The wetlines extracted from the November 1994 aerial photographs are also provided in each photograph. The distance between the wetlines from 1994 and 1997 provides a visual indication of the loss or gain in shoreline position over the period of study. Erosion measured at Codfish Park and Lighthouse South is reflected in Figures 14 and 15, while the stability at

Lighthouse North is reflected in Figure 16. Table 13 provides the average distance between the two wetlines. The distances were derived by averaging the distances measured along each of the noted profiles. These values are consistent with the shoreline changes derived from beach profile measurements as provided in Table 8. In fact, shoreline changes measured from the aerial photography tended to be lower than those derived from beach profile measurements due in part to the different wave conditions during each overflight. In 1994, the wetline was higher up on the beach due to a higher wave climate during the overflight.

Table 13
Average Distances Between Wetlines Extracted from November 1994 and February 1997 Aerial Photographs

Reach Segment	Average Distance Between Wetlines (m)
South of Codfish Park (Profiles 81-84)	-17
Codfish Park (Profiles 84-86)	-8
Between Codfish Park & Lighthouse South Systems (Profiles 86-90.6)	-6
Lighthouse South (Profiles 90.6-91.5)	-4
Between Lighthouse South and North Systems (Profiles 91.5-92)	-6
Lighthouse North (Profiles 92-93.5)	-2
North end of project (Profiles 93.5-96.5)	-5
North of project area (Profiles 96.5-99)	-2

Groundwater Elevation

During an observational period occurring in February/March 1995, CSI measured near-coast groundwater drawdown and discharge at the STABEACH™ drain sections. Groundwater elevation observations at the systems' drain sections were made discretely over varying phases of the tide, and were compared to concurrent groundwater elevation observations at piezometer locations outside of the system's influence. Piezometers used for non-dewatered groundwater elevation observations (control) were located at a longshore distance of 200 to 250 m from the termination of a system's drain section. Control piezometers were placed at horizontal locations on the profile similar to the drain section locations. Groundwater elevations observed at control locations and at operational drain section locations are presented in Tables 14, 15, and 16.

Drawdown observations provided by CSI reveal that the inflow of seawater to the drain systems varies considerably. Temporal variations in drawdown at a given system drain section are due to fluctuations in the total ocean water level and wave runup. Three main components contribute to total ocean water level:

Table 14
Codfish Park Drain Section Drawdown Observations: March 18, 1995

Time (EST)	South (m)	Supplement (m)	North (m)	Vacuum (m Hg)	Tidal Phase
08:00	0.17	-0.05	0.04	0.14	
09:00	0.21	0.09	0.13	0.10	
10:00	0.26	0.23	0.23	0.10	
11:00	0.19	0.20	0.15	0.11	
12:00	0.27	0.27	0.22	0.11	High
13:00	0.29	0.24	0.19	0.11	
14:00	0.36	0.25	0.19	0.10	
16:00	0.31	0.20	0.20	0.10	
19:00	0.26	0.23	0.19	0.10	Low
20:00	0.30	0.28	0.27	0.10	

High Tide (EST): 00:30, 12:16
Low Tide (EST): 06:10, 18:30
Winds north-northeast, 7-9 m/s

Table 15
Lighthouse South Drain Section Drawdown Observations: March 17, 1995

Time (EST)	South (m)	Supplement (m)	North (m)	Tidal Phase
08:00	0.30	1.80	0.66	
09:00	0.35	2.27	0.75	
10:00	0.45	2.52	0.70	
11:00	0.45	2.27	0.63	
12:00	0.64	2.13	0.79	High
13:00	0.45	1.96	0.64	
14:00	0.46	2.10	0.73	
15:00	0.50	2.41	0.89	
17:00	0.47	2.22	1.23	Low
18:00	0.55	2.09	1.22	
20:00	0.61	2.26	0.90	

High Tide (EST): 11:32, 23:53
Low Tide (EST): 05.25, 17:46
Winds east-southeast, 4.5 to 9.0 m/sec

Table 16
Lighthouse North Drain Section Drawdown Observations: February 26, 1995

Time (EST)	South, S1 (m)	South, S2 (m)	Supplement (m)	North (m)	Tidal Phase
09:00	0.17	0.78	2.10	1.20	
10:00	0.45	0.91	2.07	1.35	
11:00	0.59	1.02	2.23	1.5	
13:00	0.67	1.20	2.16	1.67	
14:00	0.71	1.29	2.06	1.73	Low
15:00	0.70	1.33	1.98	1.70	
16:00	0.73	1.32	1.91	1.71	
18:00	1.06	1.28	1.93	1.87	High
20:30	1.11	1.26	2.06	1.82	

High Tide (EST): 07:25, 20:11 Winds south-southeast, 4.5-9.0 m/s (am)
Low Tide (EST): 01:02, 13:35 Winds southwest, 4.5-9.0 m/s (pm)

tidal elevation, atmospheric induced surge, and wave setup. In general, for a constant discharge rate, system-induced drawdown of the near-coast groundwater elevation is minimized during periods of low ocean water elevation and maximized during periods of high ocean water elevation. For a given point in time, variations in drawdown between a given system's drain sections are controlled by the discharge per linear foot of drain section, permeability of beach material and wave runup (i.e., foreshore slope of beach profile).

Codfish Park was selected by WES for an intensive groundwater elevation observation program. Continuous groundwater elevation observations were obtained at two cross-shore transects of piezometers and directly buried pressure sensors: one transect of sensors located near beach profile transect location 85; and one control transect of sensors located at beach profile transect 87. Figure 17 presents horizontal and vertical orientation of the sensors. Data loggers sampled groundwater elevation fluctuation every 30 sec and averaged the measurements over 5 min at 15-min intervals. A barometer and internal thermometers were used to correct absolute pressure measurements for atmospheric pressure and temperature fluctuations (Curtis, Davis, and Turner 1997).

In May 1996, four pressure sensors were installed at the dewatered and control sites and operated until July 1996. An additional sensor was located approximately 100 m inland of the control transect to monitor the inland groundwater elevation. Following collection of the groundwater data, it became apparent that during the continuous observational period, the Codfish Park system was operating without use of the vacuum pump. Therefore, all

groundwater elevation measurements were collected while the system was operating below its design capacity.

Groundwater elevation data presented in Figure 18 are for measurements obtained during the time period of June 1-8, 1996. Data presented in Figure 18 are representative of observations collected from May through June 1996. Measurements were corrected for vertical sensor offset, and values presented are elevations relative to MLW. Bold curves represent observations at horizontal locations coincident with the drain location. The jagged curves represent the seawardmost sensor measurements, and the curve with the least variation in elevation (range = 0.9 to 1.1 m) represents inland groundwater measurements. Propagation of the semidiurnal tidal signal is evident at both the dewatered and control transects. A phase lag is observed between the occurrence of peaks and troughs of the tidal signal at each sensor, as the signal propagated landward. The decay and increasing symmetry of tidal groundwater fluctuations with increasing distance from the ocean boundary is evident at both the dewatered and control transects, and is characteristic of groundwater elevation fluctuations within unconfined coastal aquifers (Turner 1997).

Referring to the upper panel of Figure 18, system-induced drawdown of the near-coast groundwater is inferred by calculating the difference between concurrent groundwater elevation measurements at the sensor locations corresponding to the drain location at both control and dewatered transects. Calculated drawdown values range from 5 to 20 cm, with a distinct semidiurnal variation. Similar to drawdown calculations based on discrete observations (Tables 14-16), time series-based calculations reveal that drawdown at the drain is minimized during low tide and maximized during high tide.

Using hydrogeological observations obtained within the influence of the operational Codfish Park system as calibration data, Turner (1997) conducted a simplified modeling exercise to determine the spatial extent of the system's influence. A two-dimensional steady-state model was applied to provide qualitative insight to the horizontal extent of the system's influence. Using the MODFLOW Drain Package (McDonald and Harbaugh 1988), a 350-m-long linear drain was simulated within the model domain (Figure 19). The aquifer characteristics used are presented in Table 17. The hydraulic conductance of the interface between the aquifer and drain was adjusted until drawdown at the drain was approximately 15 cm.

Referring to Figure 19, results of the simplified simulation suggest that the longshore extent of the drawdown is limited, and the cross-shore extent of the system's influence may be significant. Simulated drawdown extends approximately 10 percent of the drain's length in the longshore direction, and approximately 30 percent of the drain's length landward. Interpretation of simulation results is merely qualitative; however, results demonstrate the potential impact of system operation on the local aquifer.

Table 17
MODFLOW Model Input Parameters

Hydraulic conductivity (m/s)	0.002
Effective porosity	0.2
Drain elevation (m)	-2.5
Aquifer depth (m)	-10
Landward (LHS) boundary	Fixed head (1.0 m)
Seaward (RHS) boundary	Fixed head (0.5 m)
Top/bottom boundaries	Fixed head (0.0 to 1.0 m, by linear interpolation)

Wave Climate

A dewatering system is designed to enhance deposition of beach material on the foreshore. The effectiveness of a dewatering system is expected to be most pronounced during natural accretionary periods of shoreline recovery. During erosionary periods, i.e. storms, when a significant amount of sand is quickly eroded from the beach, the influence of the dewatering system is expected to be negligible. It is expected that a dewatering system would be less effective in an erosive climate than in an accretionary climate. So, in evaluating the effectiveness of the dewatering systems, the tendency for offshore transport should be evaluated. The wave climate for Nantucket was analyzed to determine the tendency for offshore transport at the study areas. This was accomplished by a review of the USAE Wave Information Study (WIS) database.

WIS Database

Dean (1973) analyzed onshore-offshore sediment transport data and developed an indicator for transport. Dean found that offshore transport would occur if

$$\frac{H}{L} > \frac{\pi w}{B g T} \tag{2}$$

where

H = breaking wave height

L = deepwater wave length

w = sediment fall velocity

$B = 0.6$

g = gravity

T = wave period

To determine the frequency of offshore transport, Dean's relationship was combined with wave hindcast information for the study area. Deepwater wave hindcast information was obtained from the WIS database for location RAL2-WIS089 for the period occurring between 1956 and 1975 (Hubertz et al. 1993). Wave hindcast data were transformed from deep water to the beach using procedures outlined in Dean and Dalrymple (1984). The Rose and Crown shoals are located offshore of the study area, and reach crest elevations of -3.4 to -1.2 m MLW. Crest elevations of the shoals were used to filter extreme waves with a breaking wave criterion. Large waves will break on the offshore shoals, which are 5 to 16 km offshore, reducing the wave energy that reaches the beach.

Breaking wave conditions and 0.6-mm quartz sand were used to evaluate Equation 2. The number of occurrences of offshore transport in each month was determined. Twenty years of data were used to develop the average ratio of waves causing offshore sediment transport to all waves for each month. The results of the transport analysis are presented in Figure 20. From the figure, it is obvious that the Codfish Park and Lighthouse North and South shorelines have separate occurrence frequencies due to differences in shoreline orientation and the influence of the offshore shoals. The figure shows that Codfish Park has a tendency for offshore transport 45 to 65 percent of the time, while the Lighthouse North and South shorelines have a tendency for offshore transport 15 to 45 percent of the time with lower occurrences of offshore sediment transport occurring in June, July, and August. No criteria are available relating offshore transport tendencies to successful dewatering applications. This analysis of the sediment transport climate at Nantucket suggests that this location is a severe test for dewatering technology.

4 Environmental Impact

Groundwater Assessment

Environmental permit conditions from Federal, State, and local agencies required that a monitoring program be established to address public concern regarding the impact of STABEACH™ system operation on the local freshwater aquifer, discharge water quality, marine vegetative communities, beach meiofauna, and downdrift beach erosion. Environmental monitoring data are presented in a series of reports prepared by Fugro East, Inc., Sandwich, Massachusetts, for the SBPF. Conclusions presented by Fugro East, Inc., regarding the environmental impact of beach dewatering at Nantucket are summarized herein.

The local freshwater aquifer landward of the project site is exploited for public water supply. Therefore, the effect of system pumping, particularly at the Codfish Park location, is of primary public concern. Groundwater was assessed for seasonal variations in salinity and elevation during system operation at monitoring wells located 70, 104, 453, and 636 m landward of the Codfish Park system. No salinity was measured at any of the monitoring wells. Average groundwater elevations measured at the monitoring wells follow the trend of the regional groundwater elevation measured at the U.S. Geological Survey observation well located approximately 3 km landward of the drain. It was observed that groundwater elevations between 70 and 104 m landward of the drain respond slightly to system pumping. Interestingly, the numerical groundwater simulation using MODFLOW described previously indicated that the system could have a slight (though measurable) effect 0.100 m landward of the system. However, the important result is that observations further landward are consistent with regional groundwater elevations and so indicate no adverse influence of the system.

Discharge Water Quality

When compared to the salinity of adjacent ocean water (30-33 ppm), discharged water at Codfish Park was less salty (21-29 ppt) and was similar in salinity at Lighthouse South and North (26-33 ppt). Effluent nitrate nitrogen levels and bacterial counts were slightly higher than ambient ocean water

concentrations, exhibiting some influence of system pumping on the landward groundwater. However, the low nitrate nitrogen levels observed at Codfish Park (0.21 - 0.54 mg/ℓ) and the Lighthouse locations (0.07-0.29 mg/ℓ) have posed no concern regarding eutrophication. Compared to the bacteria standard for safe swimming (<100 count/100 ml), discharge at Codfish Park exhibited fecal coliform and streptococci counts ranging from 0 to 20 per 100 ml, and counts at the Lighthouse South and North locations were below detection. The close proximity of septic systems to the drain at Codfish Park is responsible for the detectable bacterial concentrations.

Although nitrate nitrogen and bacteria were detected in the effluent, the ambient water quality of the adjacent ocean water remains high. Fugro East, Inc., applied two U.S. Environmental Protection Agency models to assess the impacts of the effluent on the ambient nearshore water. Model results revealed negligible impact on nearshore water quality. This was due in part to high dilution factors dominated by strong tidal currents in the vicinity of the outfall.

Vegetation and Meiofaunal Communities

Annual terrestrial vegetation assessments were conducted at two of the three STABEACH™ systems. The assessments focused on species composition and overall condition of the communities to identify impacts that may be attributed to operation of the systems. It is apparent that the drawdown of the near-coast groundwater elevation with operation of the systems had no negative impact on maritime vegetation.

The variation of the intertidal meiofaunal community was evaluated to assess potential impact to the food web with system operation. A strong interannual variation in these invertebrate communities was observed at both dewatered and non-dewatered beaches. Major shifts in the distribution of taxa are not restricted to the non-dewatered beaches, and do not indicate any impact to the structure of the food web. Overall, operation of the dewatering systems did not negatively affect the density, taxonomic richness, diversity, and evenness to the meiofaunal community.

5 Summary and Conclusions

The objective of this study was to document the use of beach dewatering systems to accrete beach sand and minimize erosion, and to develop quantitative guidance for constructing and operating beach dewatering installations. This study described three independently operating dewatering systems deployed along the eastern shore of Nantucket Island, Massachusetts, and the field monitoring program established to study the influence of the system on beach processes. The monitoring program included measurements of beach morphology and hydrogeology, nearshore bathymetry, meteorology, system operation and maintenance, discharge water quality, and the effects on beach vegetation and meiofaunal communities.

The monitoring data clearly showed that the dewatering systems measurably influenced the beach groundwater table. Measurements over the drain lines showed that the amount of drawdown was greatest during the high tide. The data also showed that drawdown was influenced by the beach sediment properties. The anticipated response of the beach to the groundwater manipulation was the development of a higher, wider beach berm and steeper foreshore slope when compared to untreated regions of the shoreline. However, such a change in the beach profile was not clearly evident in the data. It was difficult to discern the overall effectiveness of the systems when compared to untreated regions of the shoreline by looking at shoreline change or beach-volume change observations in relation to periods of full operation. While shoreline stability in the region of a drain system could be observed during some monitoring periods, similar areas of stability could be found on untreated regions of the shoreline.

A trend was observed, however, when the data were analyzed by filtering the symmetrical and asymmetrical components of the shoreline and beach volume change about the centerline of the systems in what is called even-odd analysis. The results of the even-odd analysis were then matched to periods of system operation. In the project, the systems were not operated continuously due to power failures and equipment failures. Generally, the power failures occurred during storms. When equipment damage occurred, delays of weeks to months sometimes ensued before operation resumed, due to the time it took to discover the failure, identify the problem, and repair it. By evaluating percent operating time of the systems against the erosion trends around the systems as defined by

the even-odd analysis, some indications of the influence of the systems could be seen. The even-odd analysis was prepared for this project by Coastal Planning and Engineering, Inc., and is presented in full in Appendix A. Note that the even-odd analysis is a mathematical manipulation of data and is not based on physics. Therefore, the results have to be considered cautiously. Some of the conclusions that might be drawn from the analysis follow.

The first quarter of the monitoring program was disregarded from the analysis (as discussed in Appendix A), and the Codfish Park system was analyzed when it was operated more than 70 percent of the time during a given monitoring period. Results showed a relative increase in beach width within the dewatering system compared to areas outside of the system in 75 percent of the monitoring periods. (The relative increase as reflected by the even function was less than 3 m.) When the Codfish system operated less than 70 percent of the time, the analysis showed a relative increase in beach width in 25 percent of the study periods. When Lighthouse South operated more than 70 percent of the time, a relative increase in beach width occurred within the Lighthouse dewatering systems 60 percent of the time. (The relative increase as reflected by the even function was less than 3 m.) When Lighthouse South operated less than 70 percent of the time, the analysis showed a relative increase in only 33 percent of the monitoring periods.

When the systems operated more than 70 percent of the time, the beach exhibited trends consistent with a beach-nourishment model in an even-odd analysis. One explanation for this is that when operating near full capacity, the systems reduce the erosion within their limits by decreasing the amount of offshore sediment transport. This is similar to beach nourishment in that beach nourishment can be thought of as a large singular increase in the onshore sediment transport. Conversely, when the system operates less than 70 percent of the time, the majority of the monitoring periods exhibited a pattern similar to the protruding-shoreline model, or the opposite of the nourishment model. The protrusion is eroded more quickly than surrounding areas. A possible explanation for this type of behavior is that the perturbation in the shoreline created by the previously operating system eroded at a higher rate. In addition, the perturbation could be losing sediment offshore as the beach profile returns to its equilibrium shape. In short, the analysis suggested that the systems, when operated near their capacity, seem to decrease the erosion within their limits.

The shoreline receded at Codfish Park and Lighthouse South over the duration of the study, while the shoreline at Lighthouse North was more stable. It should be added, though, that during most of the monitoring period, the systems at Codfish Park and Lighthouse South were operated below capacity, while the system at Lighthouse North was operated much closer to capacity. Further, the even-odd analysis performed on the beach shoreline change data suggests that the systems have a positive influence on the Nantucket shoreline when they are operating. Conclusions based on the even-odd analysis should be considered tentative in that the technique is mathematically and not physically based. The mathematical results may have other physical interpretations.

The performance of the Lighthouse North system was particularly encouraging, in that periods of stability and accretion were frequently measured. But while this observation is encouraging, further monitoring is necessary to draw definitive conclusions about the dewatering system's performance to date. Immediately south of the system is a clay-bluff outcrop, which has eroded more slowly than the adjacent shoreline. The presence of the bluff outcrop caused the dewatering system designers to separate the Lighthouse dewatering system into two systems, one to the north and one to the south of the outcrop. The outcrop is also present in the submerged profile. Along a sandy shoreline, protrusions such as this can block the longshore transport of sediment causing it to accumulate on one or both sides of the protrusion. Based on the shoreline change data collected, it is not possible to separate the possible influence of the protrusion from that of the dewatering system. Continued monitoring of this system is recommended.

The Lighthouse South system did not operate continuously for long enough periods of time to be evaluated effectively. Additional monitoring of this system is recommended while it is operated continuously to evaluate its effectiveness.

Overall, the Codfish Park system was operated intermittently. During a brief period between March and December 1995 (9 months), the Codfish Park system operated nearly 95 percent of the time, and during that time, it was observed that the width of the beach out to the +0.61-m MLW contour was reasonably stable or accreting. As with the Lighthouse North system, the result is encouraging, but additional monitoring is necessary to effectively evaluate the performance of the system. The shoreline change data suggest the possibility of sand waves moving along the shoreline, which would at times widen the beach and at other times reduce it. However, the data collected are not conclusive in this regard. To effectively evaluate the performance of the Codfish Park system, it should be operated continuously for a longer period of time with continued monitoring.

The ecological and environmental assessment of the influence of the dewatering systems on Nantucket revealed that the systems had a minimal effect on ocean water quality and quality of the local freshwater aquifer. The observed changes in maritime vegetation and the intertidal invertebrate communities could not be attributed to system operation. However, it is advisable that potential environmental impacts be assessed in detail for future installations. A simplified modeling exercise to determine the aerial influence of system drawdown at Codfish Park revealed that the landward extent of drawdown is considerably greater than the longshore extent. Landward extent of drawdown may have adverse ramifications if the local groundwater is exploited as a public water supply, or if septic systems are within the system's influence.

Additional evaluation of laboratory and full-scale demonstrations of beach dewatering technology is required to authoritatively document engineering design criteria, and to quantitatively predict system performance. The complex interactions between the coastal aquifer, beach-face infiltration and groundwater discharge, sediment transport in the swash zone, and oceanic boundary

conditions need to be thoroughly understood before quantifiable design predictions can be assessed.

6 Commercialization and Technology Transfer

Availability of Beach Dewatering Technology

Under license to the Danish Geotechnical Institute, commercial beach dewatering systems are designed and constructed in the United States by Coastal Stabilization, Inc. The commercial beach dewatering product produced and marketed by Coastal Stabilization, Inc., is known as STABEACH™. Information regarding STABEACH™ may be obtained from:

Mr. Robert G. Kunzel
Coastal Stabilization, Inc.
100 Stickle Avenue
Rockaway, NJ 07866
Phone: (973) 983-0901

Technology Transfer

As part of the CPAR-CRDA, commercialization and technology transfer were performed by SBPF, CSI, and WES investigators. To date, four professional conference presentations have resulted from the research reported herein. Messrs. William R. Curtis and Jack E. Davis of WES jointly authored a paper entitled "Evaluation of Coastal Erosion Management via Beach Dewatering at Nantucket, Massachusetts." The paper was presented at *Coastal Zone '97*, and an extended abstract of the paper is published in the conference proceedings (Curtis and Davis 1997). Mr. Douglas W. Mann of Coastal Planning and Engineering, Inc., Boca Raton, FL, authored a paper entitled "Coastal Processes Associated with Nantucket's Beach Dewatering Systems." Mr. Mann's paper was presented at the 10th Annual Conference on Beach Preservation, and is published in the conference proceedings (Mann 1997). Messrs. William R. Curtis and Jack E. Davis of WES and Dr. Ian L. Turner of the University of New South Wales, Sydney, Australia, jointly authored a paper entitled "Independent Evaluation of a Beach Dewatering System: Nantucket Island, Massachusetts, USA." The paper was presented at the *25th International Conference on*

Coastal Engineering, and is published in the conference proceedings (Curtis, Davis, and Turner 1996). Dr. Frank Fessenden of Bentley College, Waltham, MA, authored a paper entitled "Field Test of a Beach Dewatering System for Accreting Beach Sand at Siasconset, Nantucket, MA: A Progress Report." Dr. Fessenden's paper was presented at the *31st Annual Northeastern Regional Meeting of the Geological Society of America*, and an abstract of the paper is published in the conference proceedings (Fessenden 1996). A description of the Nantucket project and an interview with CSI was published in the *Civil Engineering* trade journal (Moldonado 1996).

Articles regarding project installation, operation and monitoring have been frequently published in local newspapers, such as the *Nantucket Inquirer and Mirror*, *Nantucket Beacon*; and *Boston Globe*. Numerous mailings of a brochure prepared by CSI (Appendix B) have gone to academia, and public and private organizations. A minimum of 400 copies of this report will be distributed to USAE and Federal agency personnel, libraries, academia, and any other interested parties. In addition, CSI is available to offer advice regarding design and installation of beach dewatering technology.

Marketing Plans

CSI, with the support of the SBPF, will continue to operate and maintain the three STABEACH™ systems at Nantucket, Massachusetts, as a demonstration site. With continued operation of the beach dewatering systems, it is the objective of the partner to maintain shoreline stability within the influence of the systems. On a yearly basis, CSI will attend trade conferences within the coastal engineering and coastal management communities to present the state of the art in STABEACH™ and beach dewatering technology. By attending trade conferences, it is the goal of CSI to identify sources of project sponsorship for locations where the STABEACH™ system may be an economical and effective method for shoreline stabilization.

The opportunity to commercially install STABEACH™ systems at other coastal locations requiring shoreline stability will be actively sought by CSI. System design and installation methods will be evaluated for each project location. Based on the evaluation, a bid for design and construction of a STABEACH™ system will be submitted by CSI to the project sponsor for consideration. The cost of beach dewatering technology must be compared with conventional methods of shoreline stabilization on a project-by-project basis.

Based on CSI's experience at Nantucket, plans to develop a more robust and marketable product lie primarily in the details of construction methods. At the Lighthouse South STABEACH™ system, drain lines were abandoned due to damage of perforated polyethylene (PE) pipes and subsequent infiltration of sand. It is speculated that the damage occurred at curved sections of drain line connecting linear alongshore drain sections to the wet well during construction. Future designs will consider drain line configurations in the vicinity of the wet

well that reduce stress on the PE material during the trenchless installation process. Additionally, the chute used for deploying the drain sections on the trenchless machinery will be optimized for pipe diameters to ensure that the integrity of the PE material will not be compromised by the installation process.

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Appendix A
Even - Odd Analysis
by
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ANALYSIS OF THE EFFECTS ON THE COASTAL PROCESSES RESULTING FROM BEACH DEWATERING INSTALLATION SYSTEMS AT SIASCONSET, MASSACHUSETTS

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ANALYSIS OF THE EFFECTS ON THE COASTAL PROCESSES RESULTING FROM BEACH DEWATERING INSTALLATION SYSTEMS AT SIASCONSET, MASSACHUSETTS

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A. Introduction

In 1994/1995, three beach dewatering systems were installed in the Siasconset Beach area of Nantucket Island, MA. in an attempt to stabilize eroding shorelines. To gauge the impact of these beach dewatering systems, quarterly surveys were taken in the project area from November 1994 to May 1997. The data from the quarterly surveys through February 1997 and other relevant measurements (such as wind/wave data and dewatering pump operational data) were analyzed with a variety of techniques in an attempt to gain insight into the effect of the dewatering systems on the complex littoral system found within project area. The primary method of analysis makes use of the odd even technique to withdraw additional information from the shoreline and volume change data. In addition, the impact of beach diffusivity, the probability of cross shore sediment transport, the standard deviation of the project's contours, the evolution of the project's berm heights, and beach slopes were studied.

B. Beach Profile and Shoreline Response

The eastern Nantucket shoreline has been monitored since the early 1990's. When the dewatering systems were installed in 1994/1995, additional profile lines were added. The monitoring profile lines are shown in Figure 1. The whole numbered lines are the wading profile lines that were surveyed under previous shoreline monitoring efforts. The November 1994, December 1995, September 1996, and December 1996 profiles were surveyed to -20 feet MLW to document beach profile changes associated with the dewatering systems. All other surveys were measured to wading depth.

The November 1994, December 1995, and September 1996 surveys for profiles 86 and 97.3 are shown in Figure 2. The surveys were performed by the same survey firm with the same equipment and boat. As a result, reasonable profile closure occurs at around -20 feet MLW on profile 97.3 (Figure 2). Nevertheless, profile 86 shows significant vertical changes over the same time period. This closure problem is indicative of the closure for the southern profiles. Because the southern profiles do not close, estimation of profile volume changes in this area may not be accurate.

The lack of closure of the southern offshore beach profiles is believed to be the results of a dynamic surfzone whose coastal processes are complex. The complexity is due to wave refraction and diffraction over a spatially variable bathymetry. Near Codfish Park, a large shoal, Old Man Shoal, extends to the southeast which significantly affects the wave climate. This shoal has been previously studied and found to be dynamic (Tiffney, et al. 1991). In addition to the complex wave climate, alongshore tidal currents affect the nearshore hydrodynamics. These currents are bidirectional (with the tide) and may reach 1.6 knots and 1.9 knots at maximum ebb and flood conditions, respectively (NOAA, 1993). Sediment transport may be occurring that might not otherwise occur without the presence of the currents. Due to the lack of closure, only the data above and including mean low water will be used in the analysis of the data.

C. Description of Odd Even Analysis

Any continuous mathematical function about an origin can be broken down into an even function and an odd function. This mathematical technique has been used in the analysis of inlets on shorelines (Work and Dean, 1990) and in the analysis of a breakwater on a shoreline (Dean and Pope, 1987). The mathematical breakdown of a function y(x) into the even function E(x), and the odd function, 0(x) is

$$E(x) = (y(x) + y(-x))/2$$
$$O(x) = (y(x) - y(-x))/2$$

where x is an independent variable. The even function is symmetric about the origin (x=0) and the odd function is antisymmetric about the origin. It is assumed that applying the odd even analysis to the shoreline response and volumetric change functions will yield insight into the coastal processes and into the performance of the beach dewatering systems.

The odd even analysis applied to the Nantucket dewatering system areas utilizes shoreline position changes (the change in the MLW contour) and volumetric changes (the volume change above MLW). In theory, shoreline position or volumetric changes which result from cross shore sediment transport result in an even distribution while shoreline position or volumetric changes which result from longshore transport result in an odd function (Dean and Pope, 1987). It should be noted that the odd even analysis is only a mathematical method and is not based on physics. Therefore, the results must be interpreted carefully. The best way to interpret the functions is to compare them with odd and even function of known causes (Work and Dean, 1990). Several examples are provided in the following paragraphs.

1. Beach Nourishment and Uniform Shoreline Recession

An example which may provide an useful analogy is illustrated in Figure 3. The example shows a beach which is undergoing uniform background erosion of -20 ft./yr. The beach also contains a single property where renourishment occurs at 10 ft./yr. An odd even analysis applied at the center of the renourished property yields a zero odd function change (end losses are neglected in this example). The even function shows retreat of -10 ft./yr. within the renourished property and -20 ft./yr. on the adjacent shorelines.

2. Pocket Beach

The reorientation of a closed cell pocket beach to a new dominant wave direction is another example which can be used to demonstrate odd even analysis. As Figure 4 shows, the change in longshore transport associated with the wave direction change creates an alternating pattern of shoreline retreat and advancement. The pattern is a maximum at the extreme limits and near zero in the center.

3. Protruding Shoreline

The application of odd even analysis on a protruding shoreline undergoing uniform background erosion is shown in Figure 5. In this case, the entire shoreline is eroding at a rate of -10 ft./yr. However, the area containing the protruding shoreline is also experiencing spreading out losses of -1 ft./yr. in the protrusion center and -5 ft./ yr. at the protrusion's ends (this type of behavior has been documented in nourished beaches which protrude seaward of adjacent beaches). The material lost from the protrusion "nourishes" the adjacent beaches, resulting in a background erosion reduction on the profiles immediately adjacent to the nourished shoreline. The result is an even function which resembles the letter "w" and an odd function of zero.

4. Groin

Figure 6 illustrates another example of odd/even analysis. In this example, the study area is undergoing uniform background erosion and reorientation of the shoreline due to the installation of a groin. Application of odd even analysis to the shoreline change function yields an even function which is constant throughout the example and an odd function which is positive updrift of the groin while negative downdrift of it. The even function represents the uniform background erosion. The odd function is representative of the effects of the groin. In this case, the net effect is dominated by the odd function.

Odd even analysis requires that the spacing of the data be equal about the origin, though not necessarily uniform. Because of the varying spacing of the Nantucket beach profiles, some minor deviations were made from this requirement. While this will affect the quantitative results, the effect on the qualitative trends were felt to be small. The Lighthouse North and Lighthouse South systems were also analyzed as one system. The proximity of the two systems to each other, about 400 feet, prevented a useful analysis of each system individually. For each odd even analysis, the percentage of time that the dewatering system was operational is provided. Operation statistics were provided by Coastal Stabilization (1996, 1997).

D. Odd Even Analysis

1. Introduction

The shoreline and volumetric changes are analyzed separately at the Codfish Park dewatering system and the Lighthouse dewatering systems for each of the nine time periods. Figures 7-42 illustrate information withdrawn from each of the odd even analyses. While interpretations of the odd even data are presented, none of the odd or even signals withdrawn from the data are exactly like any known cause. Therefore, the interpretations are subjective. The data may support other interpretations as well.

To simplify the interpretation process, the assumption was made that any change in the even function within the dewatering systems was attributed to the dewatering system. However, the assumption is unlikely to be the only cause of even function changes. For example, changes in the wave field could impact the magnitude and direction of cross shore transport. However, it may be realistic to assume that over the entire study period, these fluctuations in the wave climate will result in an equal amount of erosion and accretion. One time period may see the dewatering system performance artificially enhanced by fluctuations in the natural system while another period could see performance effected negatively by the same fluctuations. Therefore, no conclusions on the effectiveness of the dewatering systems should be drawn from the analysis of one time period. The examination of the individual time periods as a whole should yield more meaningful information.

2. November 1994 to March 1995

The even functions for this period's Codfish Park shoreline response analysis (Figure 7) and volumetric change analysis (Figure 8) show an erosion reduction within the dewatering system when compared to the erosion immediately adjacent to the system. Dewatering system operation was only 56% during this time period. This pattern can be interpreted as being analogous to the pattern illustrated in Figure 3 (the nourishment example). With its alternating pattern of erosion and accretion, the odd functions are similar to the example illustrated in Figure 4 (the pocket beach example). Therefore, a possible interpretation of the data is that, during this period, the dewatering system was limiting the shoreline retreat in system area, but not preventing it. The study area was also undergoing erosion and accretion due to gradients in the longshore sediment transport. The longshore transport appears to have been from north to south.

In a manner similar to this period's Codfish Park analysis, the Lighthouse even functions for shoreline response (Figure 9) and volumetric change (Figure 10) show a reduction in the volumetric erosion and a shoreline advancement within the dewatering systems. The north and south dewatering systems operated 69% and 27% of the time, respectively. The even pattern is similar to the nourishment example. The odd pattern, also like this period's Codfish Park analysis, is analogous to the pocket beach example. The area was also undergoing erosion and accretion from changes in longshore sediment transport, which appears to have been from south to north. A possible interpretation of the data during this period of study is that the dewatering systems were limiting the erosion within their reaches. The systems may have been providing some stability in the center section of the systems.

3. March 1995 to May 1995

The even functions for volumetric change (Figure 11) and shoreline response (Figure 12) for this period's Codfish Park analysis exhibit a pattern similar to Figure 5 (the protruding

shoreline example). Although the shoreline within the dewatering system is only mildly erosional, the adjacent areas are accretional. The odd functions resemble the pocket beach example. Therefore, a possible interpretation of the data is that the dewatering system increased the shoreline erosion within its reach during this period despite the system operating at 95%. The data also supports the concept that the area was undergoing erosion and accretion from longshore sediment transport changes. The direction of littoral drift appears to have been from north to south. Since the magnitude of the odd function is greater than the even function, it is concluded that longshore transport processes were dominating.

The even functions for the Lighthouse shoreline response (Figure 13) and volumetric change (Figure 14) show that the area within the dewatering systems are accretional while the adjacent area mostly erosional. The pattern of the even functions is similar to the nourishment example. The odd functions are somewhat erratic but may indicate a south to north littoral drift. An interpretation of the data reveals that the dewatering system appeared to decrease the erosion within its limits during this time increment. In fact, the dewatering area was accretional in this case. The only information obtainable from the odd function is that the area was undergoing erosion and accretion from gradients in longshore sediment transport.

4. May 1995 to September 1995

The odd even shoreline response for Codfish Park is shown in Figure 15 while Figure 16 illustrates the Codfish Park volumetric change. The even functions for this period have higher rates of accretion within the dewatering system than outside of it. The even function patterns can be interpreted as being analogous to the nourishment example in Figure 3. The odd function patterns are not similar to any elementary example. At least two interpretations can be made of the odd functions. The general trend of the odd functions is similar to the pocket beach example. However, because the accretion (southern half) and erosion (northern half) found in the system is greater near the center than at the extreme limits of the study area, the odd functions can be interpreted as being similar to those found in the groin example (see Figure 6). If the odd function is analogous to the groin example, sediment was most likely impounded updrift of the dewatering system. In summary, one possible interpretation of the data is that the dewatering system increased the accretion rate within its limits for this period. The area was also undergoing erosion that was a result of a gradients in the longshore sediment transport. The direction of littoral drift depends on the odd function interpretation. If the function is most similar to the groin example, the drift was from south to north. If it is analogous to the pocket beach example, it was from north to south. The system operated 95 percent of the time.

Figures 17 and 18 illustrate the Lighthouse odd even shoreline response and volumetric change analyses, respectively, when the north and south systems operated 95 and 73

percent of the time. The Lighthouse even functions are similar to the pattern illustrated in the nourishment example. The shoreline response even function exhibits less erosion within the systems than outside of it while the volumetric change even function is more accretional, on average, within the system than in adjacent areas. The odd functions are slightly erratic, but are still comparable to the pocket beach example. A possible interpretation of the data is that the dewatering system was decreasing the shoreline retreat and increasing the volumetric accretion inside the systems during this monitoring period. The area was also undergoing erosion and accretion due to changes in the longshore sediment transport. Based on the odd function, the transport direction appears to have been from south to north.

5. September 1995 to December 1995

The shoreline response analysis for Codfish Park is shown in Figure 19 when the system operated 95 percent of the time. Figure 20 illustrates the Codfish Park volumetric analysis. The even functions found in these two figures have a lower rate of erosion within the dewatering systems than outside of it. This pattern can be interpreted as being similar to the nourishment example shown in Figure 3. The odd functions are not easily interpreted, but are smaller than the even functions; therefore, alongshore processes may not have been significant. Their patterns are similar to the May 1995 to September 1995 Codfish Park odd functions. As explained in that time period's section, this type of pattern can be viewed as being similar to the pocket beach example or similar to the groin example. In summary, an interpretation of this time period's data is that the dewatering system was reducing the erosion at its installation site during this time period. The study area was also undergoing small levels of accretion and erosion resulting from changes in longshore sediment transport.

The even functions for this period's Lighthouse shoreline response (Figure 21) and volumetric change (Figure 22) show a greater amount of erosion, on average, within the dewatering system than outside of it despite the system operating 95 percent of the time. The even functions are mostly accretional with exception of the middle part of the systems. The pattern is similar to the protruding shoreline example. The odd functions are similar to the May 1995 to September 1995 Codfish Park odd functions (except that the greatest erosion is in the south while the greatest accretion is in the north). They can be interpreted as being similar to the pocket beach example or the groin example. One interpretation of the data is that the dewatering system was increasing the erosion rates within its reaches during this monitoring period. The area was also undergoing accretion and erosion from changes in longshore sediment transport. The cause of these changes are open for interpretation.

6. December 1995 to February 1996

The shoreline response analysis for Codfish Park is shown in Figure 23 when the system operates only 39 percent of the time. Figure 24 illustrates the Codfish Park volumetric change analysis. The even functions found in these figures show erosion to be higher within the system than outside of it. The pattern is similar to the protruding beach example. The odd function can be interpreted as being analogous to the pocket beach example. Although the pattern is uneven, it experiences the least amount of fluctuation in the center and the greatest at the limits of the study area. This is characteristic of a pocket beach. In summary, a possible interpretation of the data is that the dewatering system, or the lack of operation of the system, increased erosion within the system during this time period. The area was also undergoing erosion and accretion as a result of longshore sediment changes. The longshore transport appears to have been from south to north.

Figure 25 and Figure 26 illustrate the shoreline response and volumetric change analyses, respectively, for the Lighthouse study area. The north system operated 95 percent of the time while the south system operated only 24 percent of the time. The volumetric change even function shows that the erosion in the area decreases within the dewatering systems. The advancement shown by the shoreline response even function increases within the systems as well. The pattern exhibited by the even functions is most similar to the nourishment example. The odd function is erratic. It does not resemble any elementary example. However, it is somewhat recognizant of the pattern shown by the May 1995 to September 1995 Codfish Park odd functions. An important difference is that May 1995 to September 1995 Codfish Park odd function experienced relatively low erosion rates at the extreme ends of the study area while this odd function did not. Therefore, no analogy can be made for this period's odd function. In summary, an interpretation of the data is that the dewatering system decreased the amount of volumetric erosion and increased the MLW advancement within its reach during this period. The area was also undergoing erosion and accretion as a result of longshore sediment changes.

7. February 1996 to June 1996

The even functions for the Codfish Park shoreline response (Figure 27) and volumetric change (Figure 28) analyses show that the average erosion within the dewatering system is slightly higher than that outside of it. The system operated only 50 percent of the time. The pattern exhibited by the shoreline response even function resembles the protruding shoreline example (see the December 1995 to February 1996 Codfish Park explanation). The volumetric response even function also has the characteristic "w" pattern found in the protruding shoreline example. The odd function is difficult to analyze, but is most similar to the December 1995 to February 1995 Lighthouse odd function. Like that odd function, this period's odd function is open for interpretation. Therefore, a possible interpretation of the data is that the dewatering systems increased erosion within their limits during this

period. The area was also undergoing erosion and accretion resulting from longshore sediment transport gradients.

Figure 29 and Figure 30 show the shoreline response and volumetric change analyses, respectively for the Lighthouse study area when the north and south system operated 95 percent and 0 percent of the time, respectively. The even functions also resemble the protruding beach example. The even function did not perform as well within the dewatering systems as it did outside of it. The odd function is somewhat erratic but can be interpreted as being similar to the pocket beach example. Therefore, an interpretation of the data is that the dewatering system increased erosion within the installation site during this time increment possibly due to the shutdown of the south system. The area was also undergoing erosion and accretion from gradients in the longshore sediment transport. The littoral drift appears to have been from north to south.

8. June 1996 to September 1996

The shoreline response and volumetric change analyses for Codfish Park are shown in Figure 31 and Figure 32, respectively. The dewatering system operated 65 percent of the time. The even functions show an increase in the erosion within the dewatering system relative to the areas adjacent to it. Both even functions show the maximum erosion occurring at the system center. The pattern exhibited by even functions is similar to the protruding beach example. The shoreline response odd function is most similar to the December 1995 to February 1996 Lighthouse odd function pattern. An important difference is that the majority of the erosion is in the south and the majority of the accretion is in the north. Like the December 1995 to February 1996 Lighthouse pattern, this period's shoreline response function can be interpreted different ways. The volumetric response odd function resembles the pocket beach example. In summary, an interpretation of the data could be that the dewatering system, or lack of operation, was increasing the erosion within its boundaries during this time period. The area was also undergoing accretion and erosion as a result of gradients in the longshore transport. However, the cause of the gradients is open for interpretation.

Figure 33 and Figure 34 illustrate the Lighthouse study area functions for shoreline response and volumetric change, respectively. The north and south dewatering systems operated 95 percent and 42 percent of the time, respectively. The even functions show greater erosion inside the dewatering systems than outside of them. Both the volumetric and shoreline response pattern are similar to the protruding beach example. The odd function is irregular and is somewhat reminiscent of the December 1995 to February 1996 Lighthouse odd function. In summary, a possible interpretation of the data is that the dewatering system, or its operation level, was increasing the erosion rate within its boundaries. The area was also experiencing erosion and accretion from gradients in the longshore sediment transport.

9. September 1996 to December 1996

The shoreline response analysis for Codfish Park is shown in Figure 35. Figure 36 illustrates the Codfish Park volumetric change analysis. During this time period the system operated only 62 percent of the time. The even functions performed better within the dewatering system than adjacent to it. The shoreline response's even function showed the greatest advancement within the system. The area within the dewatering system also gained volume while the shoreline outside the system lost volume. The even patterns resemble the nourishment example. The odd function is somewhat similar to the Lighthouse December 1995 to February 1996 odd function. Like the Lighthouse December 1995 to February 1996 odd function, this period's odd function is also open for interpretation. In summary, a possible interpretation of the data is that the dewatering system increased the accretion within its limits during this period. The area was also undergoing erosion and accretion due to gradients in the longshore sediment transport. The mechanism creating these gradients is open for interpretation.

The even functions for the Lighthouse shoreline response (Figure 37) and volumetric change (Figure 38) show a decrease in the erosion within the dewatering systems while the systems operated 95 percent of the time. The pattern of the even functions can be interpreted as being similar to the nourishment example. The odd functions are irregular and of smaller magnitude than the even functions. They are unlike any elementary example. However, they remotely resemble the odd functions found in the Lighthouse December 1995 to February 1996 example. In summary, a possible interpretation of the data is the dewatering system decreased the erosion within the system limits during this time period. The area was also undergoing erosion and accretion due to gradients in the longshore sediment transport. The mechanism creating these gradients is open for interpretation.

10. December 1996 to February 1997

Figure 39 and Figure 40 illustrate the shoreline response and volumetric change, respectively, for Codfish Park. The dewatering systems operated 95 percent of the time during this time period. The even functions shown in these figures exhibit a greater amount of accretion within the dewatering system than outside of it. The even functions have a pattern which can be interpreted as being similar to the nourishment example. The odd function is similar to the Lighthouse December 1995 to February 1996 odd example. In summary, a possible interpretation of the data is that the dewatering system was increasing the accretion within its limits during this period. The area was also undergoing accretion and erosion from gradients in the longshore sediment transport. The cause of these gradients is open for speculation.

Figure 41 shows the Lighthouse study area shoreline response when the systems were operating 95 percent of the time. The volumetric change for the Lighthouse study area

is illustrated in Figure 42. The even functions exhibit erosion near the center of the systems and show accretion elsewhere. The net effect, even if the profile between the two systems is excluded, is a lower amount of average accretion within the systems than outside of them. The pattern is similar to the protruding beach example. The odd functions are similar to those found in the Lighthouse December 1995 to February 1996 analysis. In summary, a possible interpretation of the data is that the dewatering systems were decreasing the accretion inside their limits during this period. The area was also undergoing accretion and erosion as a result of gradients in the longshore sediment transport. However, the mechanism creating these gradients is open for interpretation.

E. Impact of the Dewatering Systems Based on Even Odd Analysis

1. Introduction

After examining the previous analysis, at least two trends relevant to the impact of the dewatering systems become apparent. First, the dewatering systems appear to be more effective when they operate near their capacity. Although this trend is not surprising, it is relevant to the analysis because only one of the three dewatering systems operated near full capacity for the entire study period. If the dewatering systems are not functioning, they cannot be expected to alter the littoral processes of the project area. Secondly, the direction of littoral drift seems to correlate with the dewatering system functioning rate. When the pumps operate near their capacities, the majority of the periods experienced net longshore sediment transport from north to south at Codfish Park. However, a net south to north transport was present for the majority of the monitoring periods when the pumps operated at lower rates. The Lighthouse study area experienced similar trends. This is significant due to the potential impacts on adjacent areas if the systems are influencing longshore sediment transport.

2. Correlation of Dewatering System Operation and Dewatering System Performance

The dewatering systems seem to impact the beach more favorably if the pumps are operated near their capacities. The systems' operations and beach responses are summarized in Table 1. When the Codfish system operates at a rate over 70%, the even functions show an increase within the dewatering systems relative to the areas outside of the systems in 67% of the monitoring periods. When the Codfish systems operate under 70% capacity, the even functions only show a relative increase in 40% of the study periods. When Lighthouse south operated at greater than 70 percent of the time, the even functions show an increase within the dewatering systems relative to the areas outside the dewatering systems 60 percent of the time. When Lighthouse south operated less than 70 percent of the time, the even functions showed an increase only 50 percent of the time (Table 1).

The gap between these two statistics widen if the first monitoring period is ignored. During the first period of study, the dewatering systems were being installed. Therefore, none of the systems operated near peak capacity when the period as a whole is analyzed. For example, the Lighthouse North system had an overall capacity of 69% for the quarter despite operating at a 95% rate (95% is full capacity) after completing installation on December 20, 1994. Because the date of the initial survey does not coincide with the beginning of full operation by the systems, the first quarter may not be relevant in this type of analysis. If the first quarter is ignored, the even functions show relative increases within the Codfish dewatering systems during 75% of the monitoring periods in which the pumps operated over 70% of the time. However, when the Codfish pumps operated less than 70% of the time, only 25% of the periods (not including the first quarter) showed a relative even function increase within the system areas. At the Lighthouse system, operating the south system at greater than 70% of the time yields increasing even functions 60 percent of the time. If the south system is not operated 70 percent of the time, an even function increase occurs only 33 percent of the time.

A possible explanation of the shoreline behavior exhibited within the dewatering systems can be made by making use of the odd even examples previously presented in the "Description of Odd Even Analysis" section. The majority of the periods in which the systems operate over an 70% rate exhibit an even pattern similar to the nourishment example shown in Figure 3. Therefore, one explanation of this behavior is that when operating near full capacity, the systems reduce the erosion within their limits by decreasing the amount of offshore sediment transport (or increasing the amount of onshore transport). This is similar to a nourishment in that a beach nourishment can be thought of as a large singular increase in the onshore sediment transport. However, when the system operates for less than 70% of a period, the majority of the quarterly analyses exhibit an even function whose pattern is similar to the protruding shoreline example shown in Figure 5 or to the opposite of the nourishment example.

A possible explanation for this type of behavior is that the apparent bulge in the shoreline created by the previously operating system is now being eroded at a higher rate due to diffusion. In addition, the apparent bulge could be losing sediment offshore as the beach profile returns to its equilibrium position. The patterns which are similar to the opposite of the nourishment example could be representative of offshore transport while the "w" shaped protruding shoreline patterns could indicate diffusion losses. In summary, the systems when operated near their capacity seem to decrease the erosion within their limits. However, when the systems are operated at less than their capacity, erosion within the system limits seems to increase. The increase is most likely due to diffusion or cross shore equilibration.

5. Summary

Based on the preceding limited analyses, the following processes seem to be occurring at Nantucket's dewatering systems.

A. A spatially uniform shoreline recession which dominates the net shoreline response at times.

B. A dewatering system induced shoreline advancement within the limits of the system when the system is operating near its capacity.

C. A recession of previously trapped sand by diffusion processes or profile equilibration when the dewatering systems are not operating near capacity.

D. The possibility of an alongshore reorientation of the shoreline or possible trapping of the littoral drift by the dewatering system when the system operates.

E. The possibility of a return to the initial shoreline orientation by releasing the trapped sand when the dewatering systems are not operating near capacity.

F. Beach Dewatering & Beach Fill Diffusion

The preceding odd even analysis provides insight into the possible processes that may be affecting the beach and shoreline response at the dewatering systems. The analysis also showed that the systems had little net positive effect on the shoreline. If the dewatering systems did not cause positive effects on the shoreline (advancement), understanding the ineffectiveness is also important. Review of the data developed the following hypothesis: A beach stabilized by a dewatering systems must overcome the effects of beach fill diffusion.

Consider an artificially created beach that is stabilized (littoral drift is constant) with a dewatering system. If the dewatering system is turned off, the beach will erode due to end losses, beach profile equilibration, and background erosion. It has been shown (NRC, 1995) that the fill diffusion rate can be described as being proportional to the ratio,

$$\frac{L}{(Gt)^{1/2}}$$

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$$\frac{L}{(Gt)^{1/2}}$$

where L is the length of the beach fill, t is and G is the diffusivity which is proportional to the breaking wave height to the 2.5 power. From this ratio, longer beach fills subject to lower waves last longer. In the case of a dewatered beach nourishment, the dewatering system must overcome the diffusion processes. Therefore, it follows that longer dewatering systems should perform better than shorter systems. Systems exposed to lower waves should also perform better. For the system in Nantucket, early results indicate better performance at the Lighthouse systems than at Codfish Park. This is consistent with the system length discussion. If systems are not achieving positive shoreline changes, the wave climate (diffusivity) may be too severe.

1. Wave Climate Analysis

Beach dewatering systems have had limited application to date, with only 2 long term installations in the U.S. As a result little data has been collected that explains the systems success or failure. The process whereby the dewatering systems reportedly operates is to collect the onshore sediment transport and reduce the offshore transport. Since the direction of onshore - offshore sediment transport in the absence of beach dewatering is governed by the wave height, wave period, and sediment size, the wave climate was analyzed to determine the probability of offshore sediment transport at Nantucket Island. This was accomplished in two phases: 1) a review of locally collected wind data, and 2) a review of the WIS database.

2. Wind Data

A wind gauge has been in place on the Siasconset shoreline to record local weather conditions. The gauge is located above the Siasconset bluff. The wind data from October 1991 to September 1992 was analyzed to determine the frequency of strong onshore winds and the time between onshore wind events. The results are shown in Table 3.

A 15 mph wind criteria was selected as a representative wind speed which would probably be accompanied by waves large enough to cause offshore sediment transport. Table 3 shows that the eastern shoreline of Nantucket is exposed to onshore winds greater than 15 mph at least 4 to 5 times per month. The exception is the months of June and July. The maximum time span between onshore events indicates that the strong onshore winds occur nearly on a weekly basis. If it is agreed that the rate of offshore transport is greater than onshore transport (Fredsoe and Deigaard, 1992), then the wave climate may contribute to a tendency for net offshore transport.

Table 3

Frequency of Onshore Wind Events
at Siasconset, Nantucket Island

MONTH	NUMBER OF EVENTS WITH WIND GREATER THAN 15 MPH AND DIRECTED ONSHORE	GREATEST NUMBER OF DAYS BETWEEN ONSHORE WIND EVENTS
Oct. 91	4	10
Nov. 91	5	18
Dec. 91	4	19
Jan. 92	5	9
Feb. 92	5	9
Mar. 92	8	7
Apr. 92	6	10
May 92	10	11
Jun. 92	3	24
Jul. 92	2	18
Aug. 92	4	13
Sep. 92	8	8

3. WIS Database

Dean (1973) analyzed onshore-offshore sediment transport data and developed an indicator parameter for onshore offshore transport. Dean (1973) indicated that if

$$\frac{H}{L} > \frac{\pi w}{Bgt}$$

were H is the breaking wave height, L is the deep water wave length, w is the sediment fall velocity, B=0.6, g is gravity, and t is the wave period, offshore transport would occur. To determine the frequency of offshore transport this relationship was used along

with the revised Atlantic wave hindcast for the Nantucket area (RAL2-WIS 089). The wave hindcast data was shoaled and refracted from deep water to the beach using the procedures outlined in Dean and Dalrymple (1984). Because of the Rose and Crown shoals which reach elevations of -11 to -4 feet MLW, all waves were filtered using a breaking wave criteria to reduce the extreme waves. Large waves will break on the offshore shoals which are 3 to 10 miles offshore, thereby reducing the wave energy that reaches the beach. Linear shoaling and refraction calculations were performed using a computer program for all waves to provide an estimate of the nearshore wave climate.

The breaking wave conditions and 0.60 mm quartz sand were used to evaluate the Dean (1973) transport criteria. The number of occurrences of offshore transport in each month was determined. Twenty years of data were used to develop the average ratio of waves causing offshore sediment transport to all waves for each month. The results are shown in Figure 43. The Codfish Park and Lighthouse shorelines have separate occurrence frequencies because of the significant difference in shoreline orientation and wave filtering, by the offshore shoals.

The Codfish Park wave climate indicates that offshore sediment transport occurs 45 to 65 percent of the time with little apparent summer conditions. The Lighthouse shoreline experiences offshore transport conditions 15 to 45 percent of the time with lower occurrences of offshore sediment transport occurring in June, July, and August. Nevertheless, the Nantucket Island wave climate may not be conducive to beach dewatering if the goal is to build/widen the beach. This conclusion is directly opposite the conclusion of Beachler (1993) when he found that the wave climate of Nantucket was similar to the wave climate at Torsminde, Denmark, the site of a successful temporary installation of dewatering technology.

While this analysis shows a propensity for offshore sediment of 0.60 mm sand, the beaches could equally be assumed to be in dynamic cross-shore equilibrium over the long term (see profile 97.3 in Figure 2). Dean's transport indicator may be only an <u>estimate</u> of the likelihood of dewatering system success for a given wave climate.

G. Beach Profile Stability

A potentially useful measure of shoreline stability is the standard deviation of shoreline position. It could be expected that if the dewatering technology stabilizes the beach, or enhances the recovery after storms that the shoreline would be expected to have less erosion and accretion than adjacent non dewatered shorelines. Therefore, since its position is more constant than a dynamic shoreline, the standard deviation of its positions about the mean position would be less. To calculate the dewatering system impact on stability, the standard deviation of the MLW and +6 MLW contour positions for each profile in the study area were calculated. The results are shown in Table 4.

Table 4

Beach Profile Variability

Study Area	0.0 Ft. MLW Contour Average Standard Deviation (FT.)	+6 FT. MLW Contour Average Standard Deviation (FT.)
Codfish Dewatering System	16.9	13.5
Lighthouse Dewatering System	6.8	8.0
All Profiles Outside Dewatering Systems	10.8	11.0
6 Profiles Adjacent to Codfish System	18.5	14.6
6 Profiles Adjacent to Lighthouse North System	6.3	6.1
6 Profiles Adjacent to Lighthouse South System	11.5	12.9

Table 4 indicates that the Lighthouse dewatering system profiles exhibit less fluctuations than all profiles outside the dewatering systems when compared at the 0.0 FT. MLW and 6.0 ft. MLW contours. Table 4 also shows that when the Lighthouse dewatering profiles are compared against their adjacent profiles, the results are mixed. No significant improvements occur at the Lighthouse systems when compared to the profiles adjacent to Lighthouse north. The profiles adjacent to Lighthouse south showed greater fluctuations (less stability) than the profiles within the dewatering system.

Codfish Park dewatering system appears to have increased the stability of the beach when compared to adjacent profiles. While this may be interpreted as an indicator of system success, the magnitude of the improvement is not great.

H. Berm Height Dynamics

Another measure that could be indicative of a dewatering system's impact is berm height change. The berm elevation of each profile was measured (from the survey data) at a point approximately 15 ft. seaward of the November, 1994 dune position. This point was assumed to be representative of the berm. The elevation at these stations were tracked throughout the study period. Table 5 summarizes the results. The range in berm elevations was determined by subtracting the lowest berm elevation from the highest berm elevation for each profile. This is an indication of the berm elevation dynamics.

Table 5

Berm Elevation Analysis

Area	Average Berm Elevation Change Nov 94 to Feb 97 (FT)	Average Berm Elevation Range (FT)
Codfish Dewatering System	-2.1	4.7
Lighthouse Dewatering System	-0.6	3.2
All Profiles outside Systems	-0.9	3.6
6 Profile to Adjacent to Codfish System	-2.3	5.1
6 Profiles Adjacent to Lighthouse North	-1.3	3.3
6 Profiles Adjacent to Lighthouse South	-1.5	4.6

Table 5 indicates that the Codfish Park Dewatering System beach profiles experienced slightly less berm elevation loss than untreated adjacent profiles and the range of berm elevations was also slightly less. Nevertheless, the dewatering system was unable to stabilize the berm as 2.1 feet of sand was lost.

At the Lighthouse dewatering systems, the beach experienced less berm elevation loss and less berm range than adjacent profiles which may be viewed as a measure of success of this system. Nevertheless the beach elevation lost 0.6 feet where the dewatering systems exist.

I. Beach Slope Change

In theory, dewatering systems increase the stability of a shoreline by decreasing the net offshore sediment transport. In the absence of other forces, an increase of onshore transport coupled with a decrease in offshore transport will create a steeper beach slope. A steepening of the beach slope was observed in another dewatering system installation site which was deemed successful (Dean, 1990). Based on theory and observation, a dewatering system that is affecting the shoreline positively might be expected to increase the beach slope within its reaches.

Beach profile slopes were determined for each profile as the linear slope from the +6 ft. MLW station to the -1 ft. MLW station. This analysis was performed at each system during the time period when the system operated at its highest level. For Lighthouse South and Codfish Park, the highest operation level was between March and December 1995. For Lighthouse north, the highest operation level was from November 1994 to February 1997. The slope results are

presented in the form of the cotangent of the angle that the beach slope makes with the horizontal (Table 6).

Table 6

Beach Slope Changes

Survey Area	Average Cotangent Slope Initial	Average Cotangent Slope Final
Lighthouse North (LHN)	6.9	6.3
LHN Adjacent Profiles [1]	6.7	6.3
Lighthouse South	6.2	6.0
LHS Adjacent Profile [1]	7.0	6.0
Codfish Park (CFP)	7.6	6.4
CFP Adjacent Profiles	8.8	7.9

[1] 6 Profiles immediately adjacent to system.

Lighthouse north profiles showed a mild steepening from cotangent values of 6.9 to 6.3, but the adjacent profiles showed similar trends. Lighthouse south profiles steepened from cotangent values of 6.2 to 6.0, but the adjacent profiles steepened more from 7.0 to 6.0. At Codfish Park the profiles steepened as well from cotangent values of 7.6 to 6.4, but the adjacent profiles also steepen from 8.8 to 7.9. While the total steepening adjacent to Codfish Park is not as steep (7.9 to 6.4) as within the dewatered system, the magnitude of the steepening is approximately the same.

The beaches on Nantucket are steep when compared to beaches throughout the United States where a beach face slope of 1V:10H to 1V:20H may be typical. The natural steepness at Nantucket is due to the wave climate and the coarse grain quartz sediment (0.60mm). While the beaches at the dewatering systems steepened while the systems operated, the difference in steepening between dewatered and adjacent profiles is minimal. Steepening does not appear to have occurred as a result of dewatering. Wave climate changes, or beach face armoring as a result of erosion may have occurred.

J. Conclusions

The analyses of the survey data and of the Nantucket wave climate lead to the following preliminary conclusions regarding the application of beach dewatering at Nantucket's eastern shoreline.

1. The dewatering systems appear to be lessening the shoreline recession by reducing the background recession rate.

2. The dewatering systems must be operated greater 70 percent of the time to be effective.

3. A shoreline reorientation occurs which may result in alongshore impacts. Dewatering systems may not be benign to alongshore sediment transport.

4. The severity of the Nantucket wave climate may not be conducive to beach dewatering because of the tendency for offshore sediment transport.

5. Some beach profile steepening has occurred but it does not appear to be caused by the dewatering process.

6. Berm elevations have lowered in the study area with the dewatering system reducing the lowering slightly. Nevertheless, the loss of berm elevations due to storms has not been prevented by the dewatering system nor has enhanced berm recovery been evident.

Further evaluation of the Nantucket beach profile data is recommended. Comparative evaluations of the Nantucket systems with the Sailfish Point, Florida system are also recommended.

K. Acknowledgment

The support of the U.S. Army Corps of Engineers, Coastal Engineering Research Center (CERC) is appreciated. The results and opinions presented are those of Coastal Planning & Engineering, Inc. and are not necessarily the opinion of CERC.

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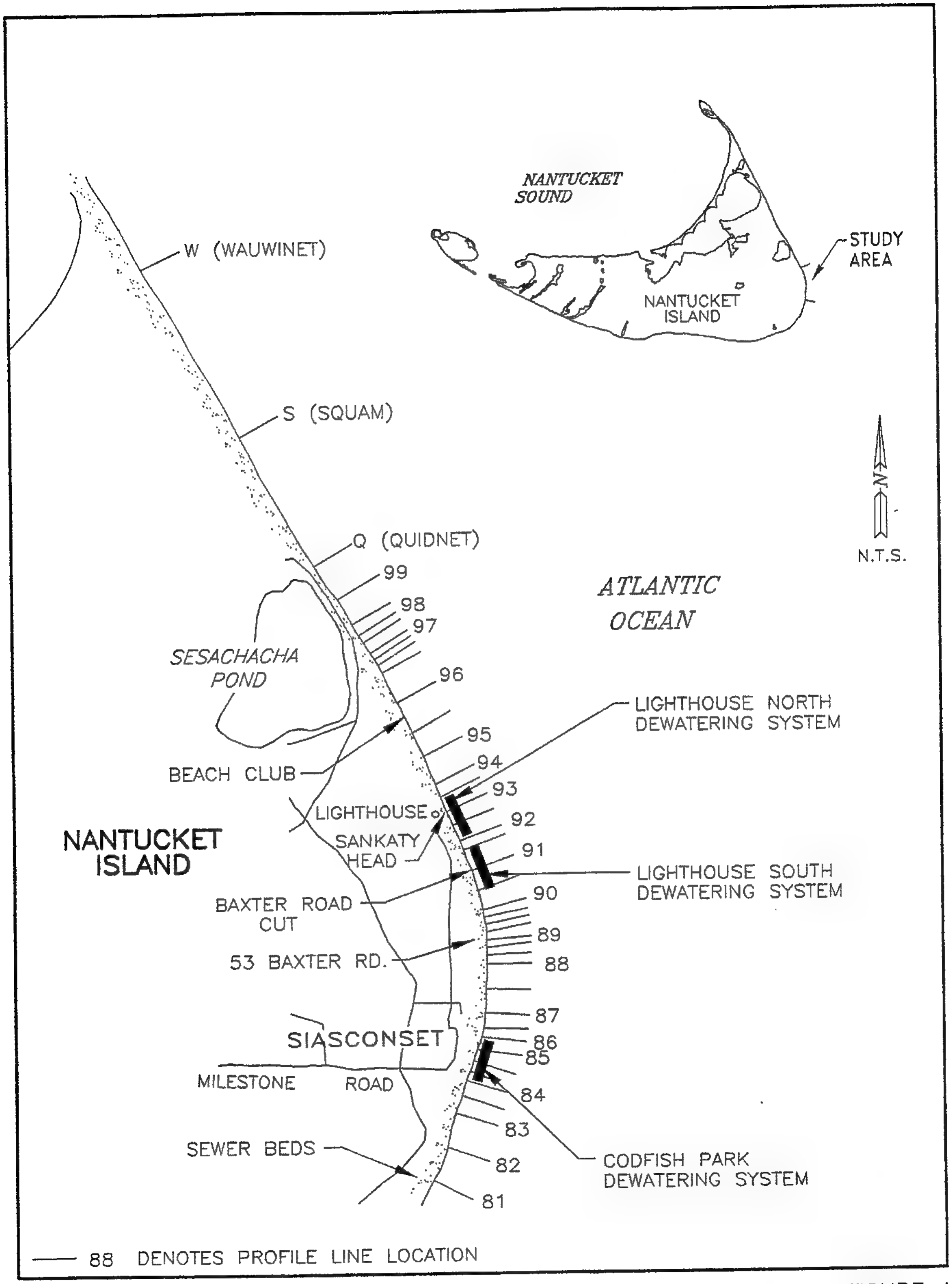


FIGURE 1

LOCATION MAP

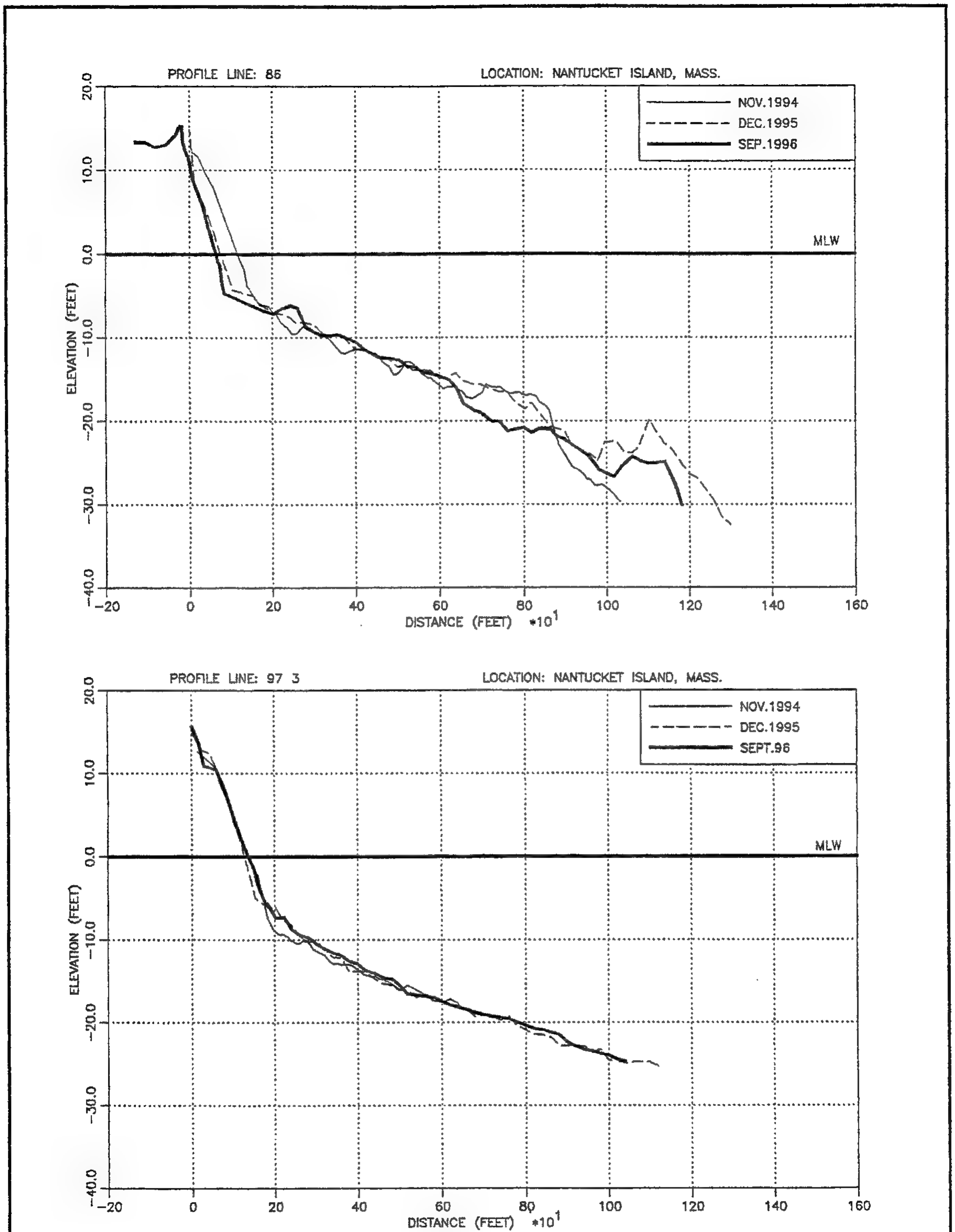


FIGURE 2

BEACH PROFILE CLOSURE EXAMPLE CROSS-SECTIONS

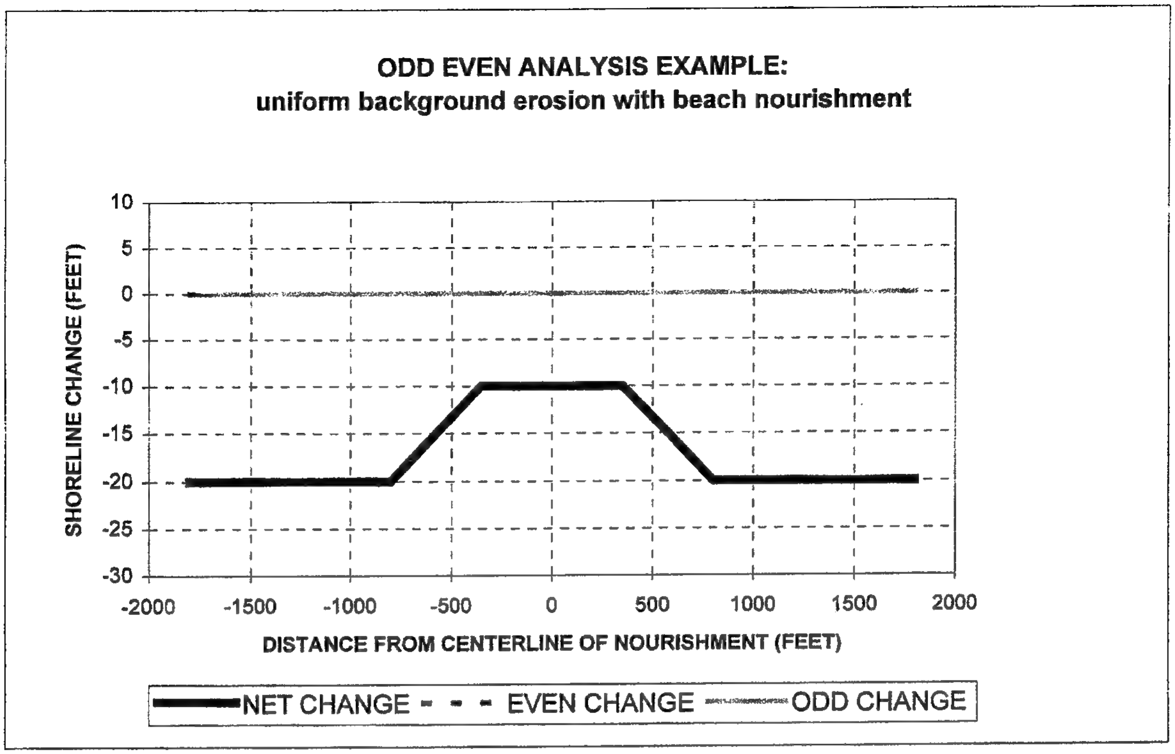


FIGURE 3

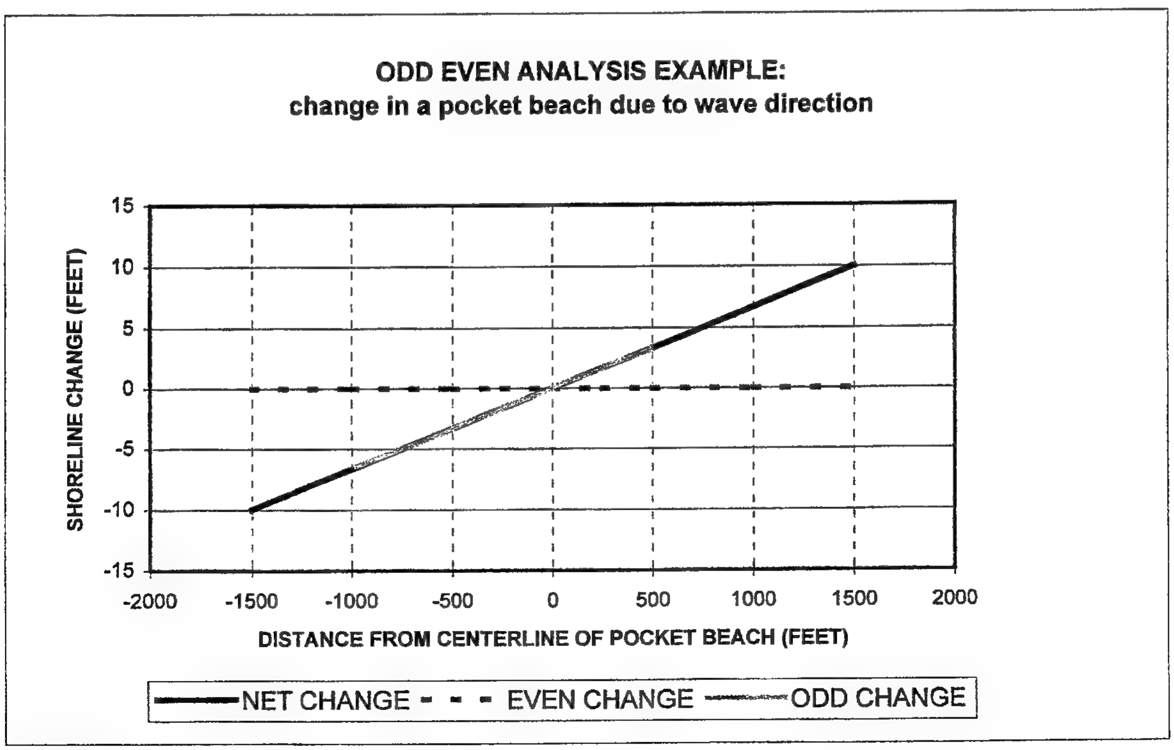


FIGURE 4

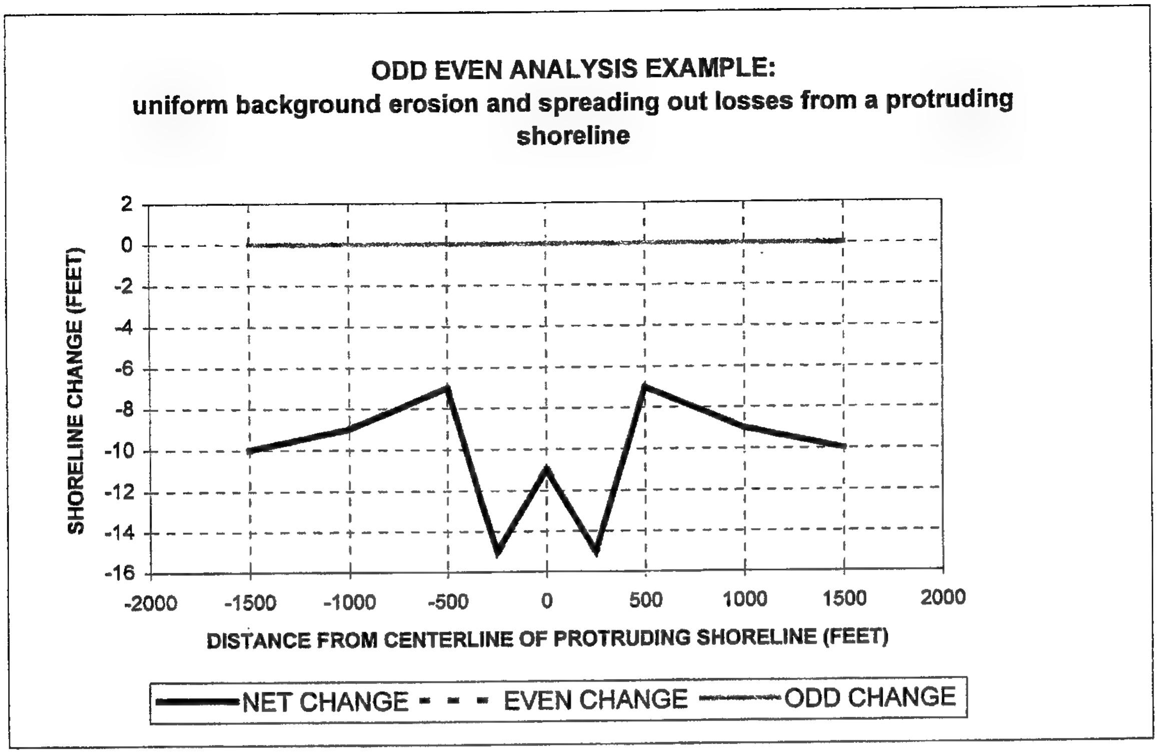


FIGURE 5

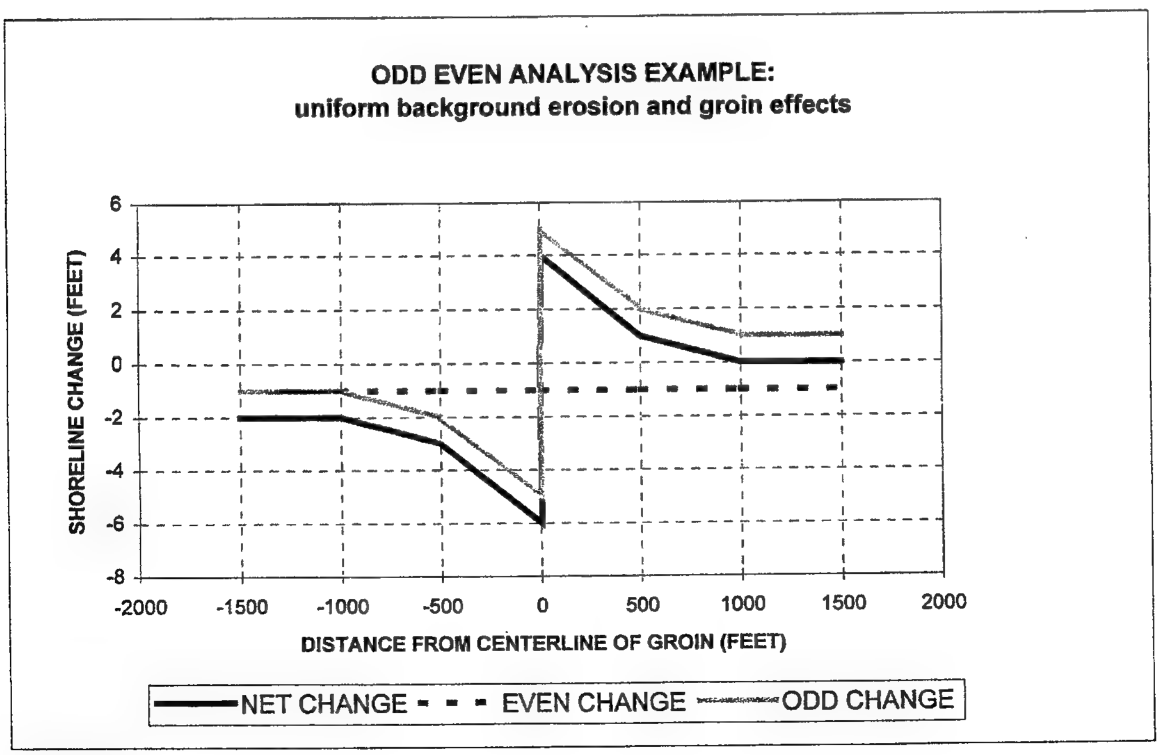


FIGURE 6

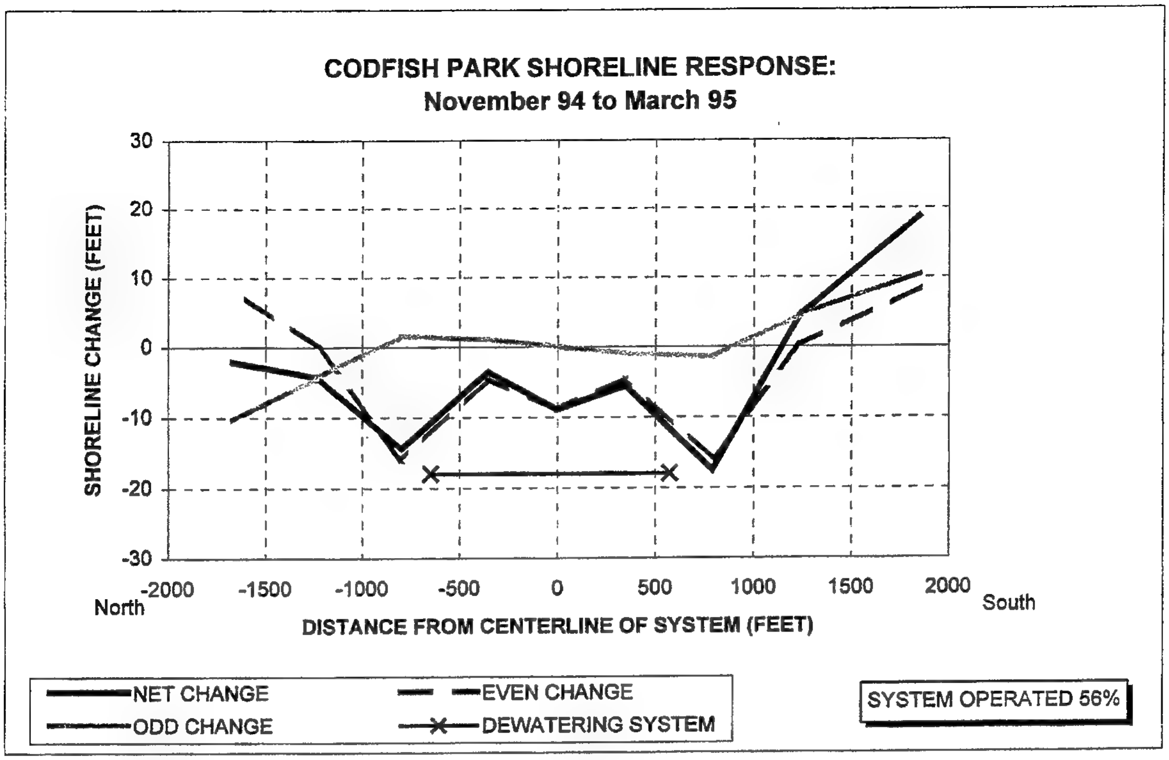
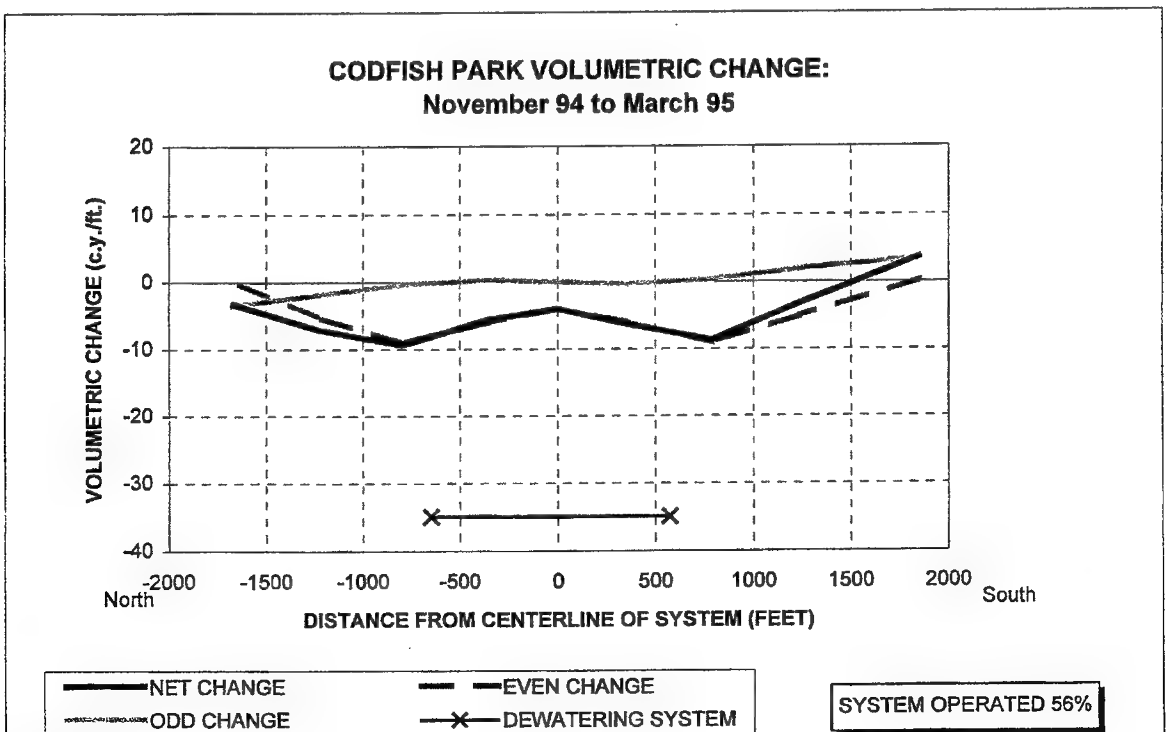


FIGURE 7



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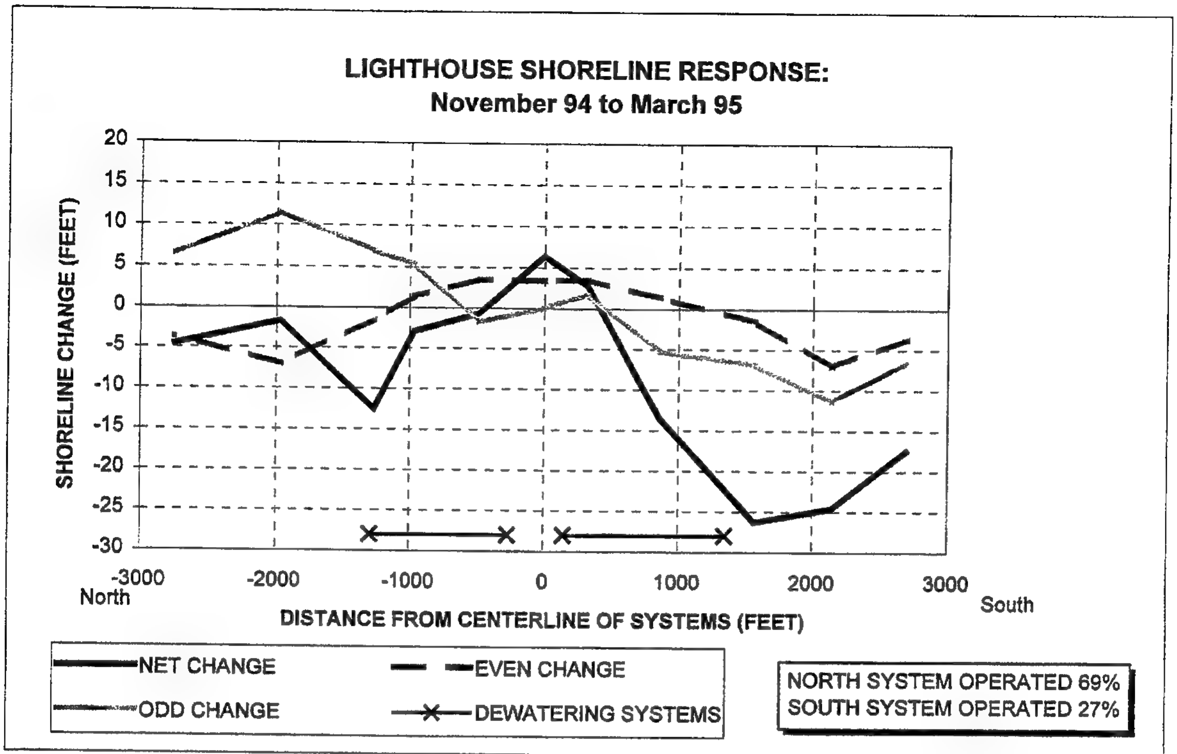

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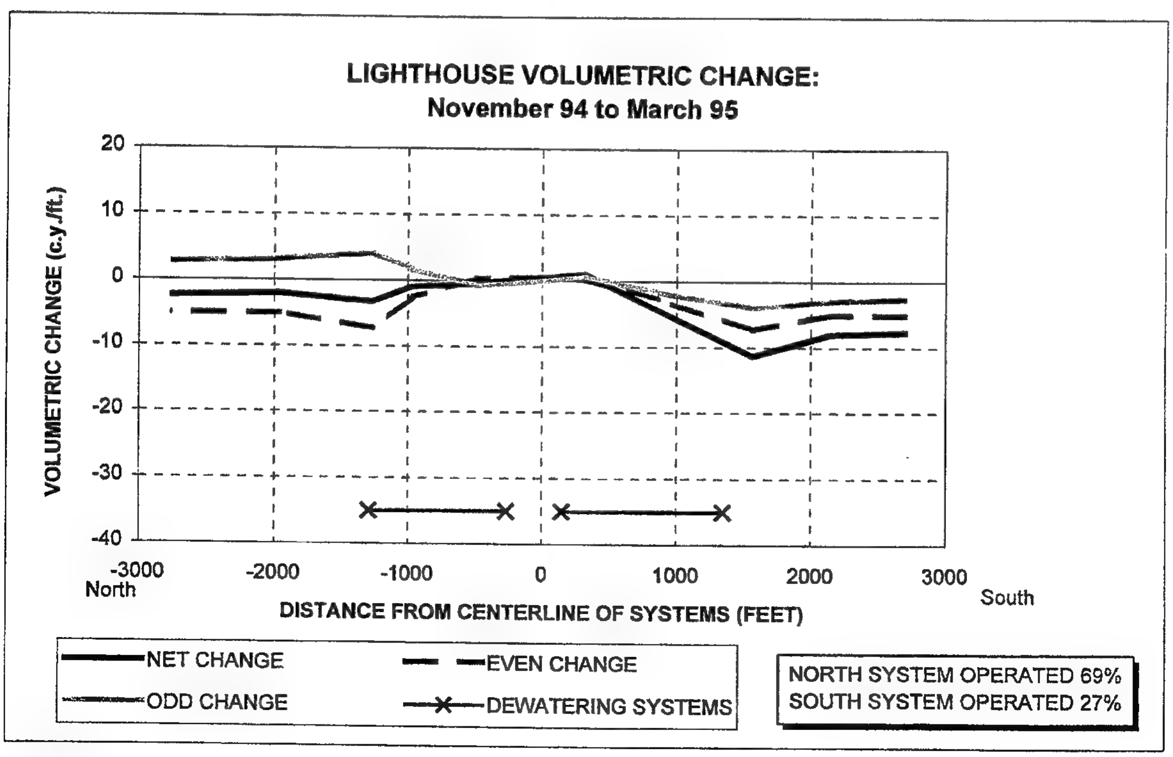

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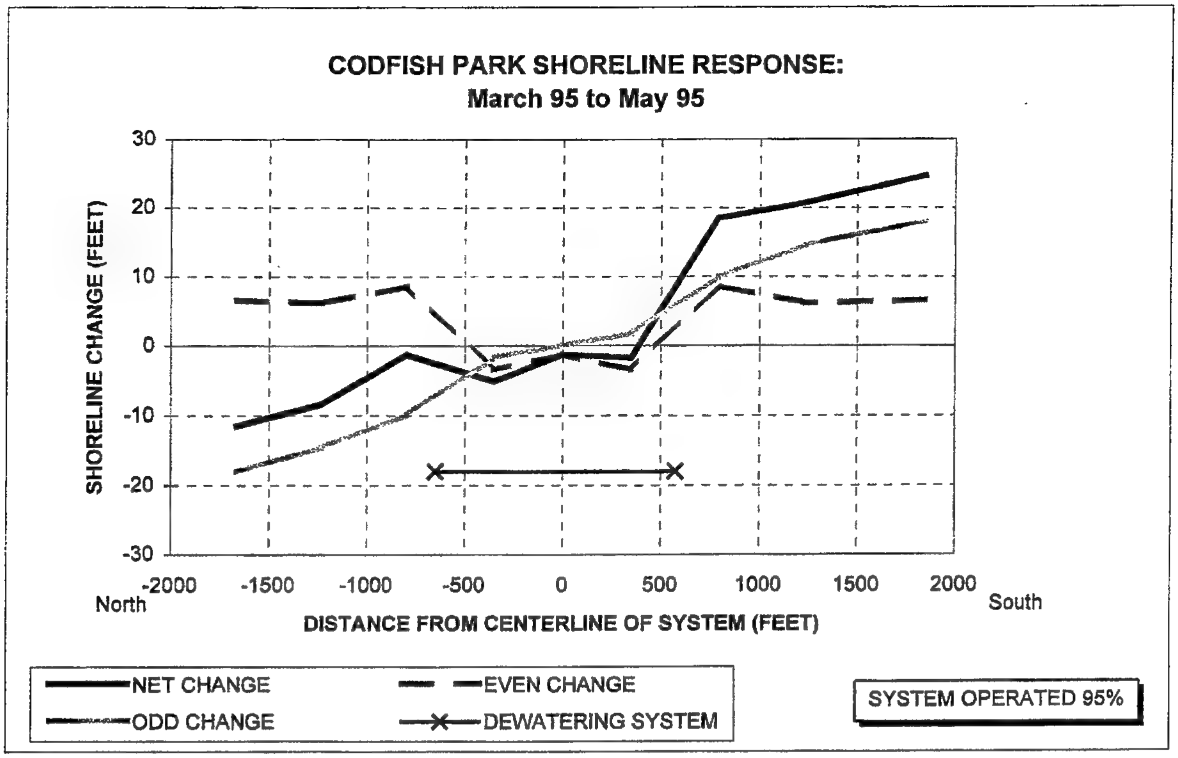

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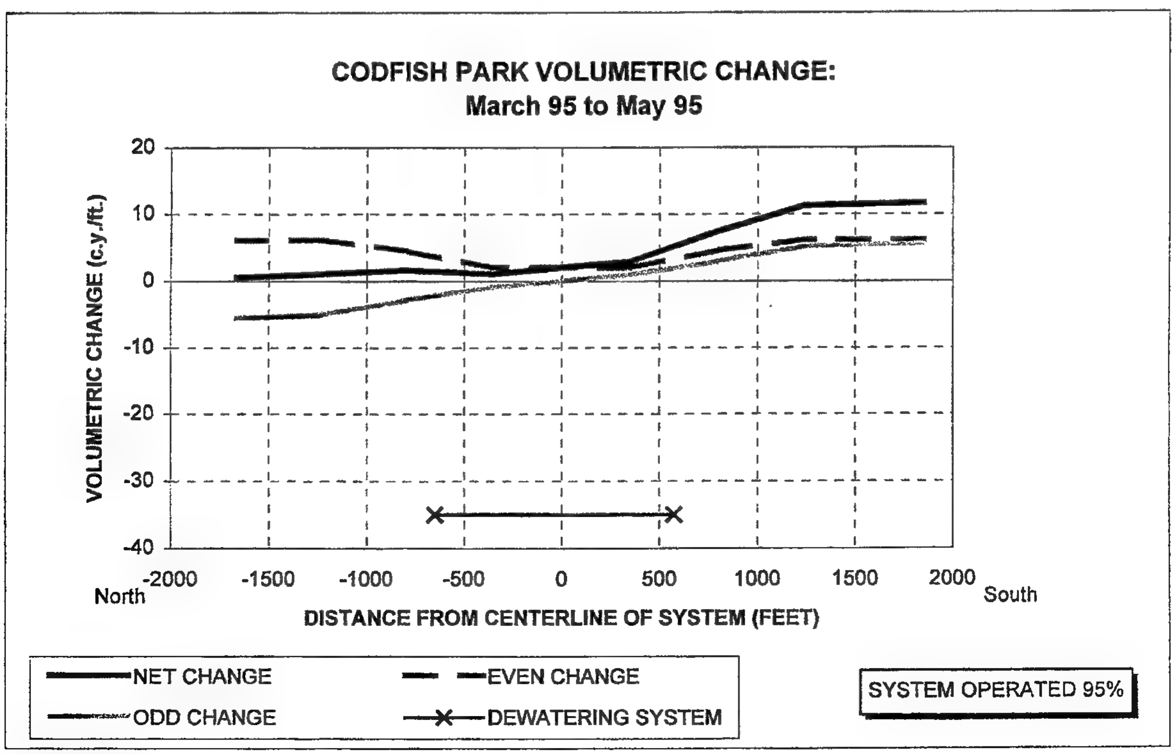

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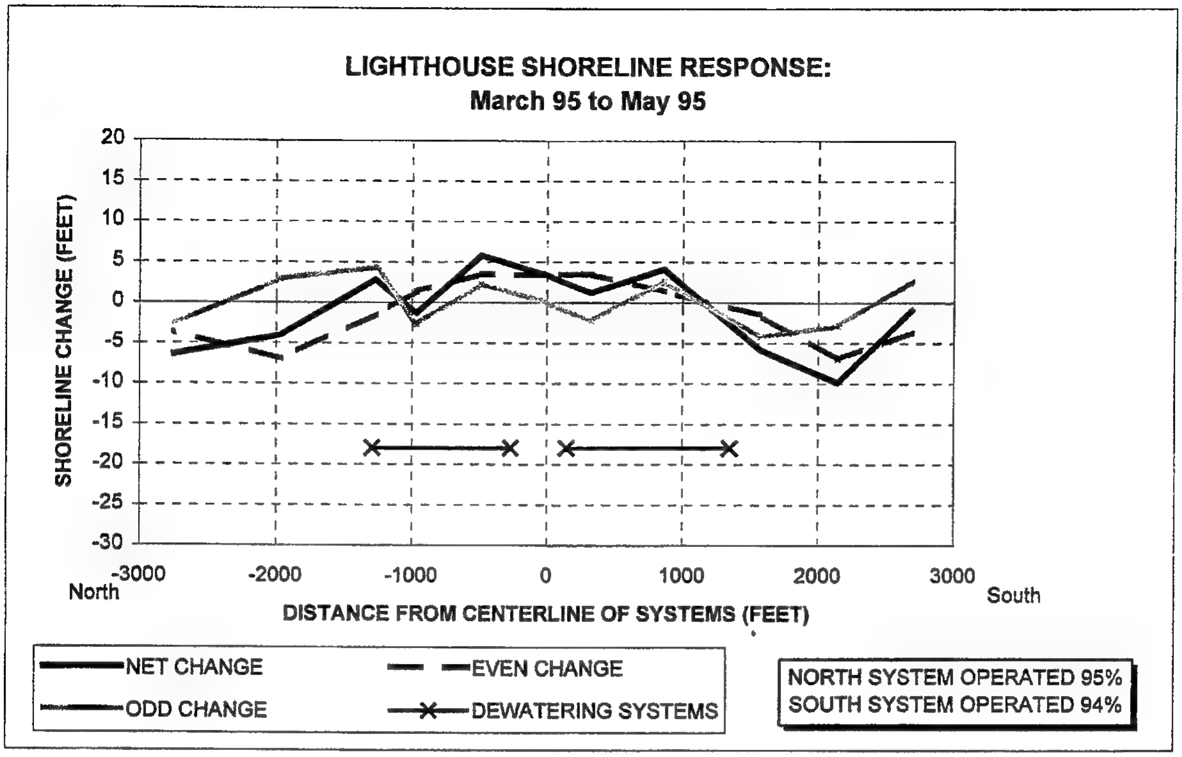

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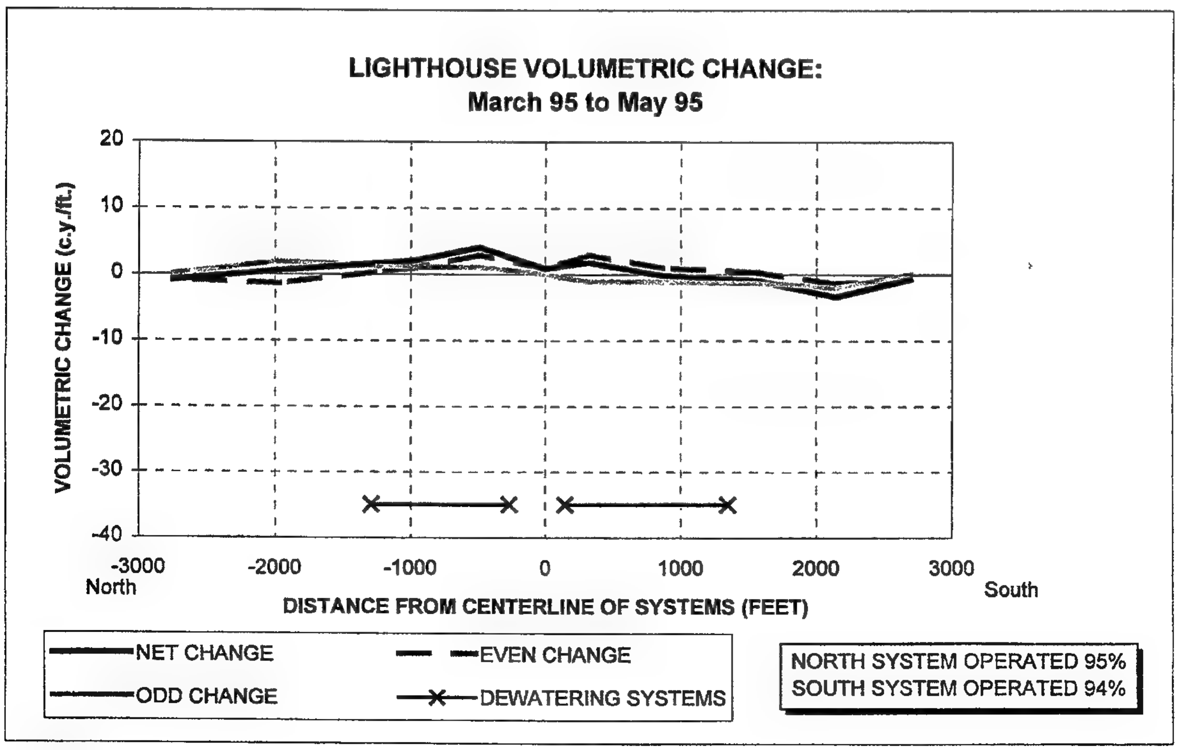

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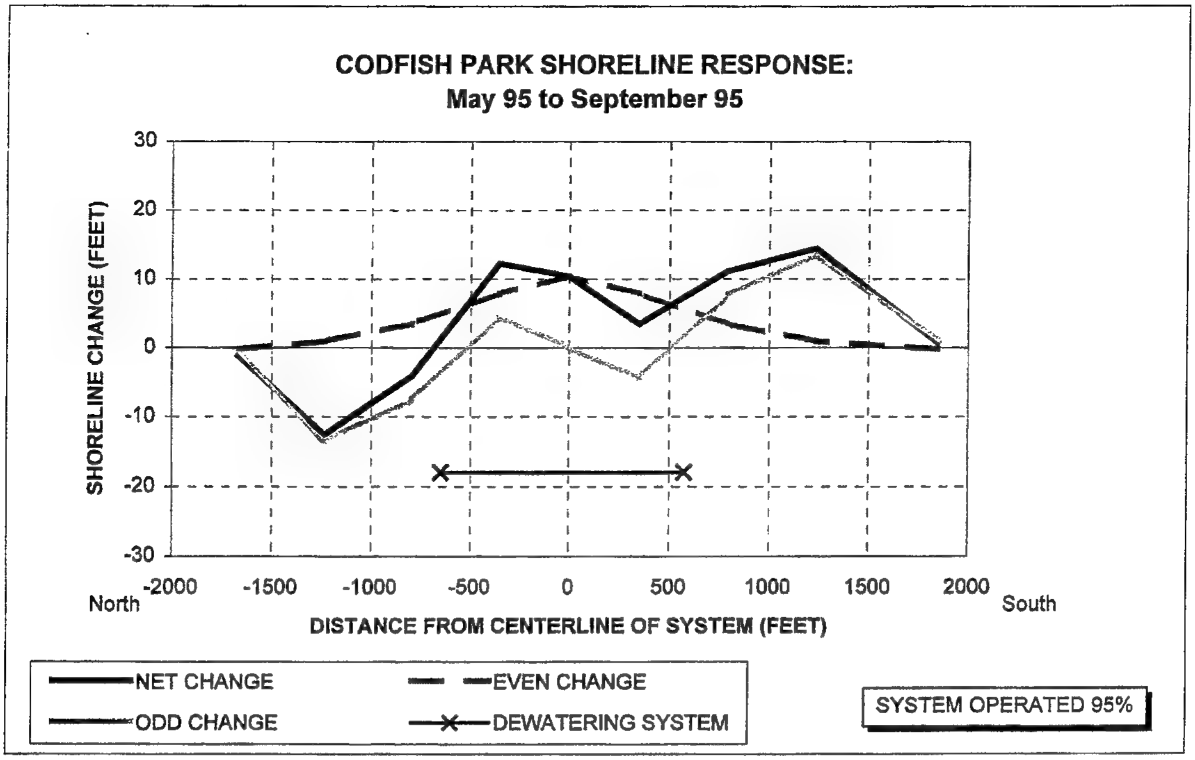

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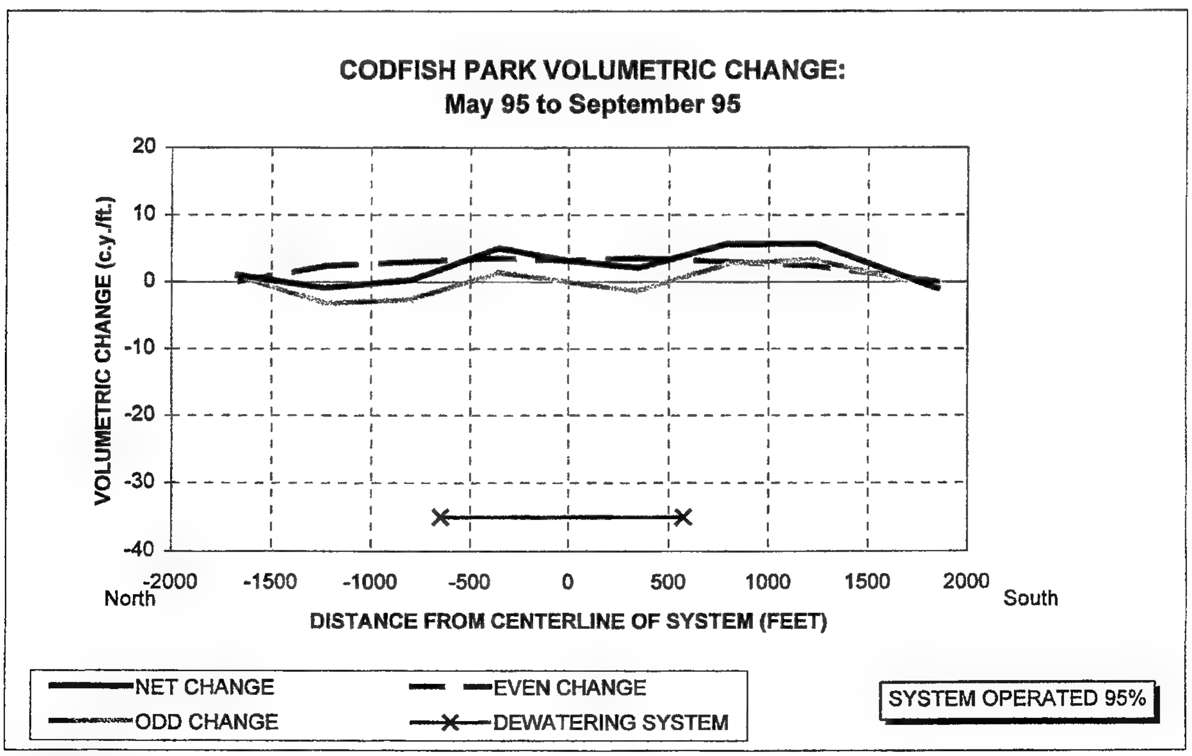


FIGURE 16

ANALYSIS OF THE EFFECTS ON THE COASTAL PROCESSES RESULTING FROM BEACH DEWATERING INSTALLATION SYSTEMS AT SIASCONSET, MASSACHUSETTS

Prepared For:

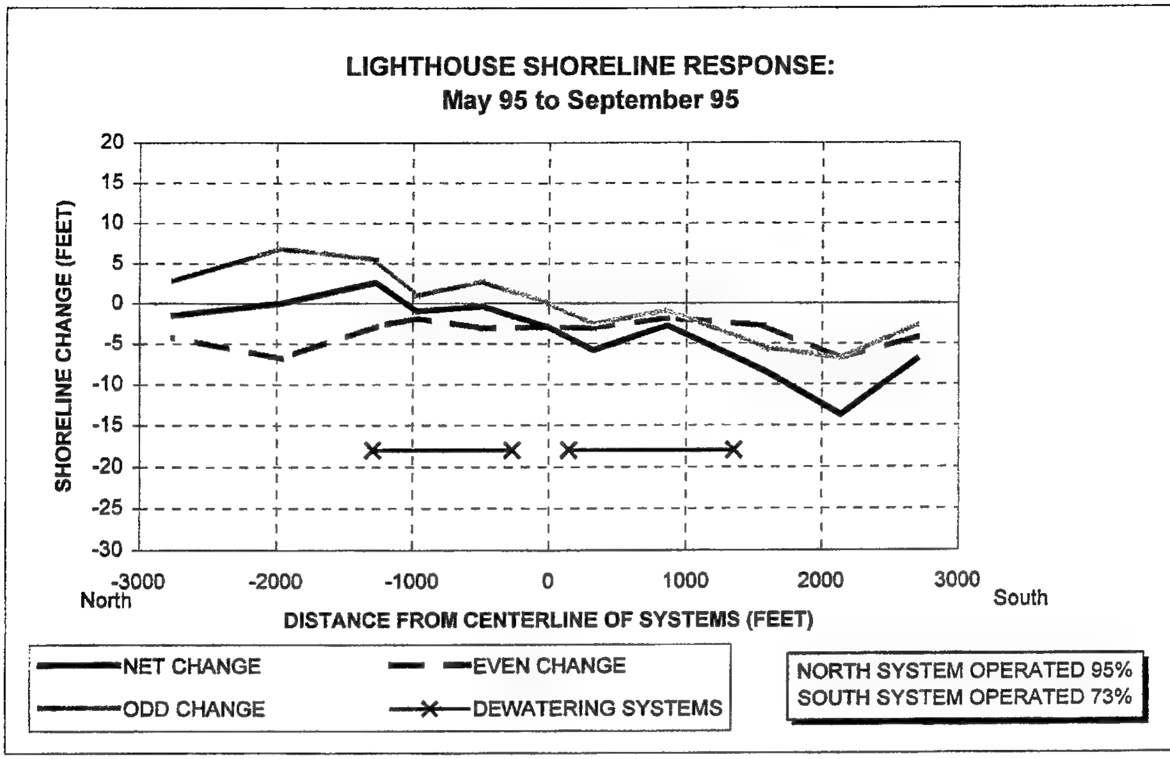
Coastal Engineering Research Center
Waterways Experiment Station

Prepared By:

Coastal Planning & Engineering, Inc.
2481 N.W. Boca Raton Boulevard
Boca Raton, Florida 33431

June 1997

COASTAL PLANNING & ENGINEERING, INC.



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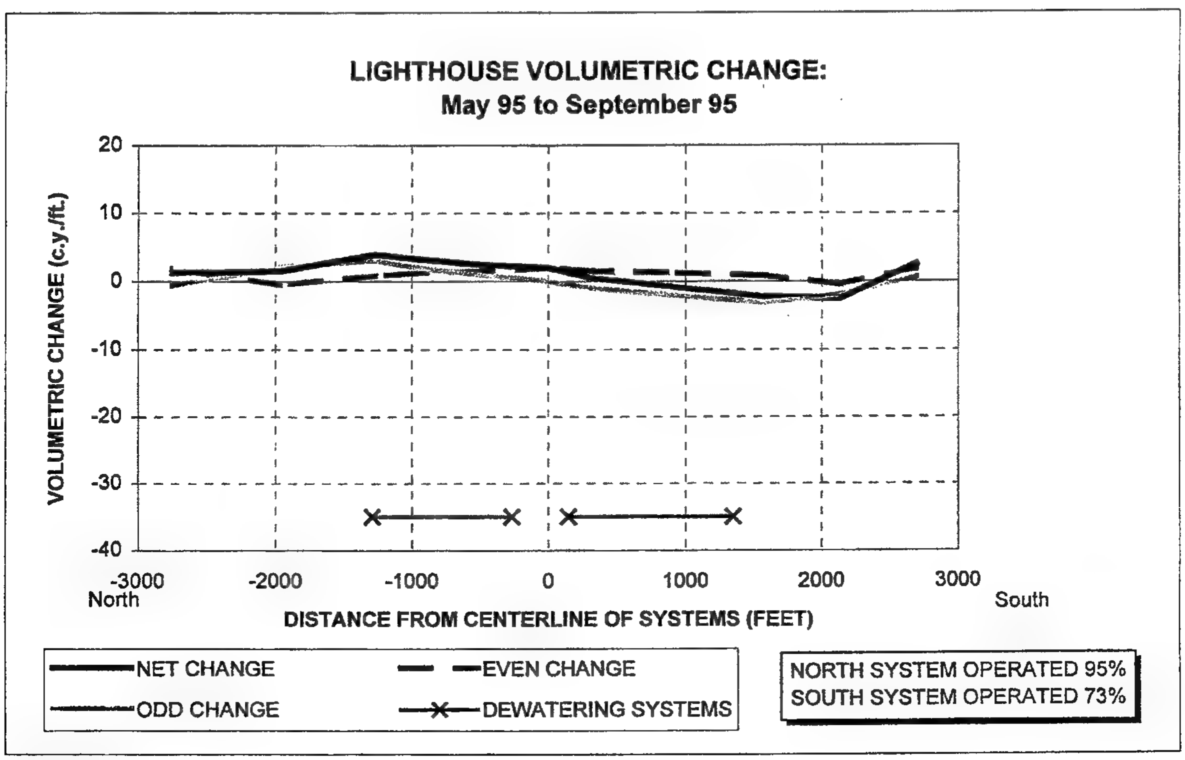

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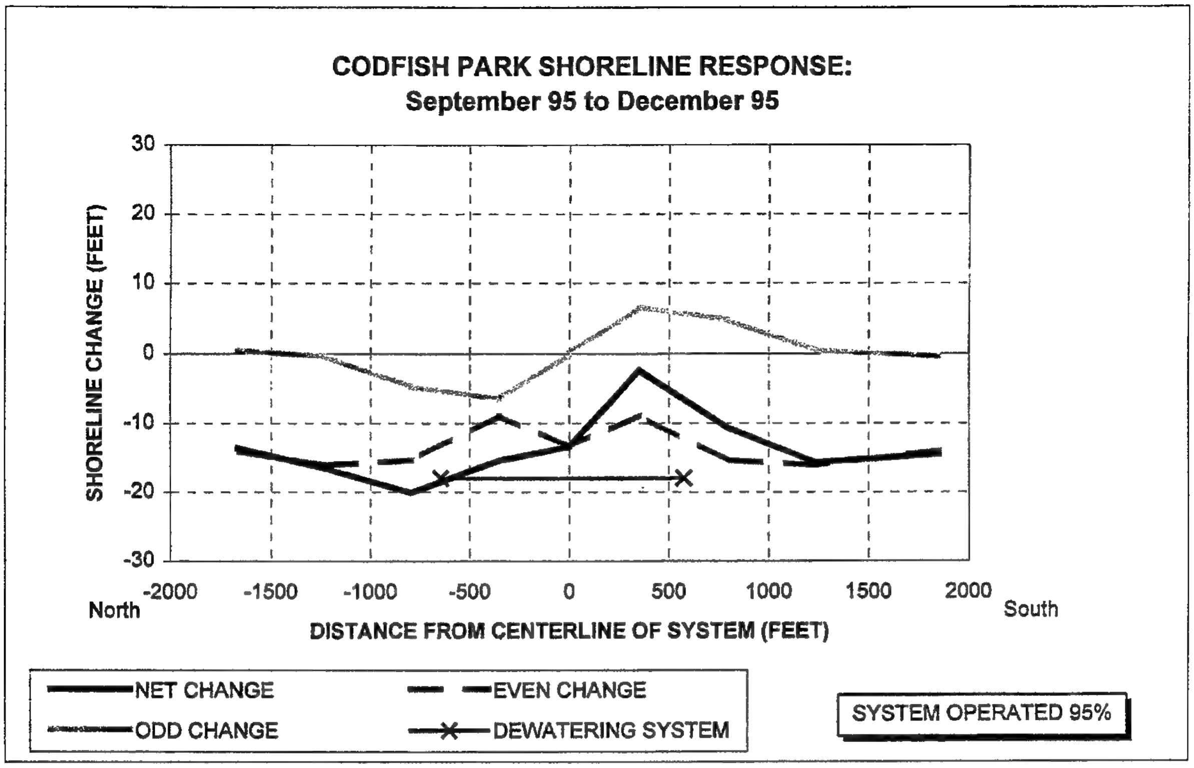

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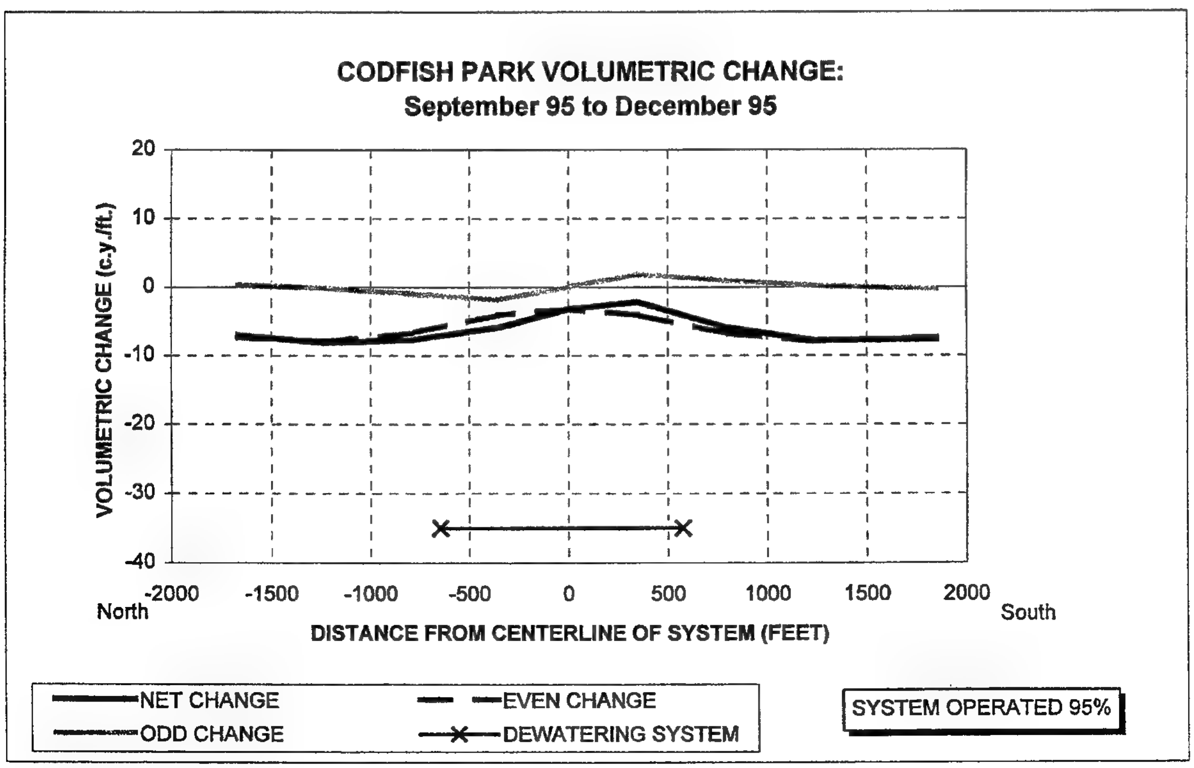

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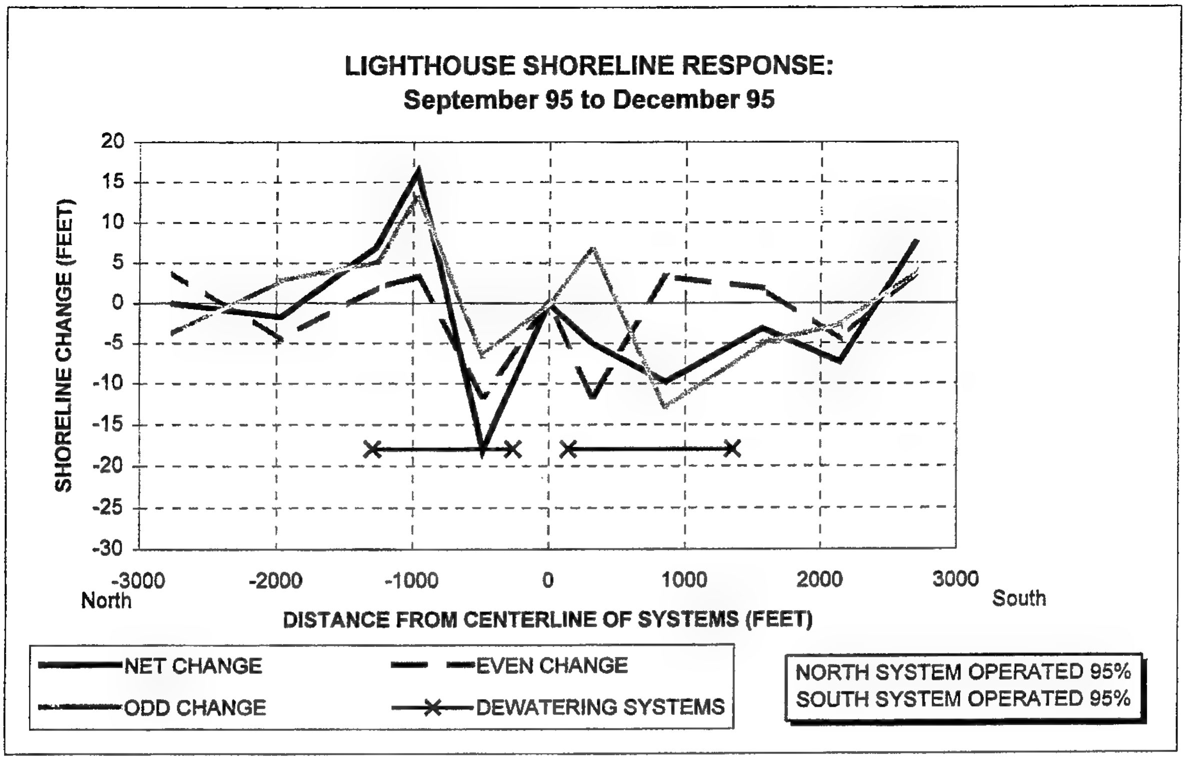

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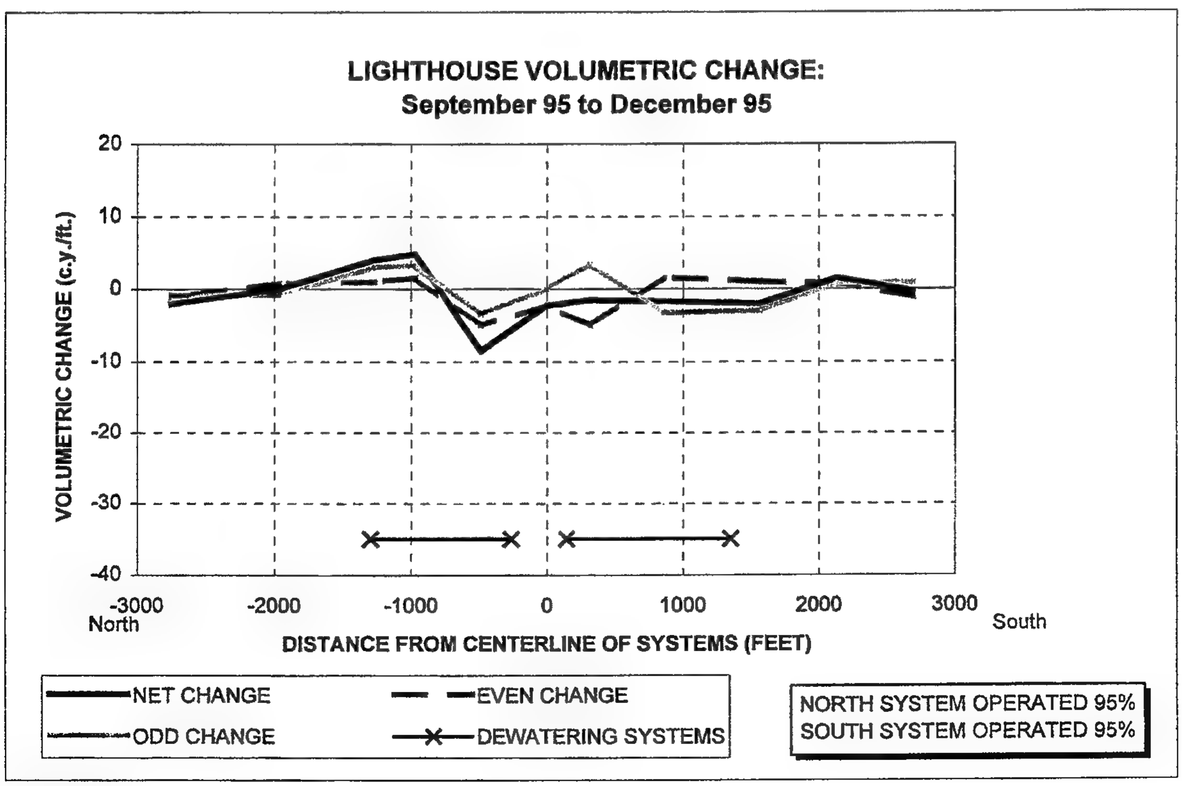

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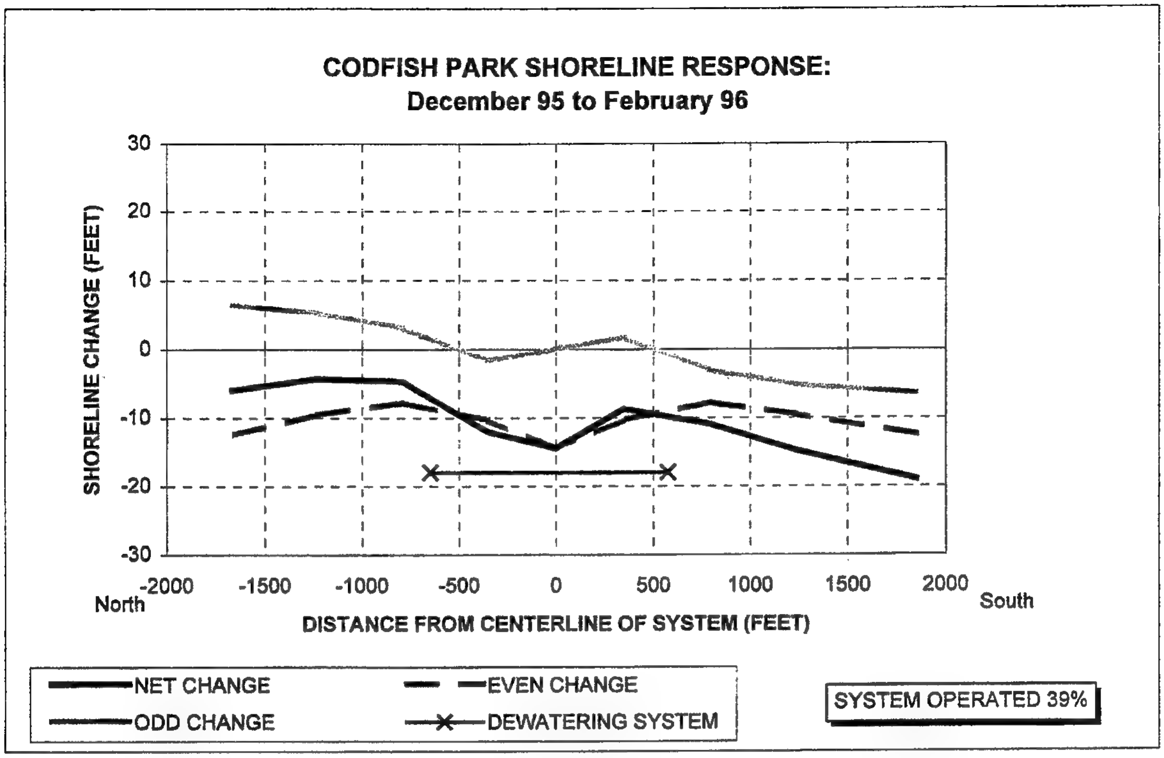

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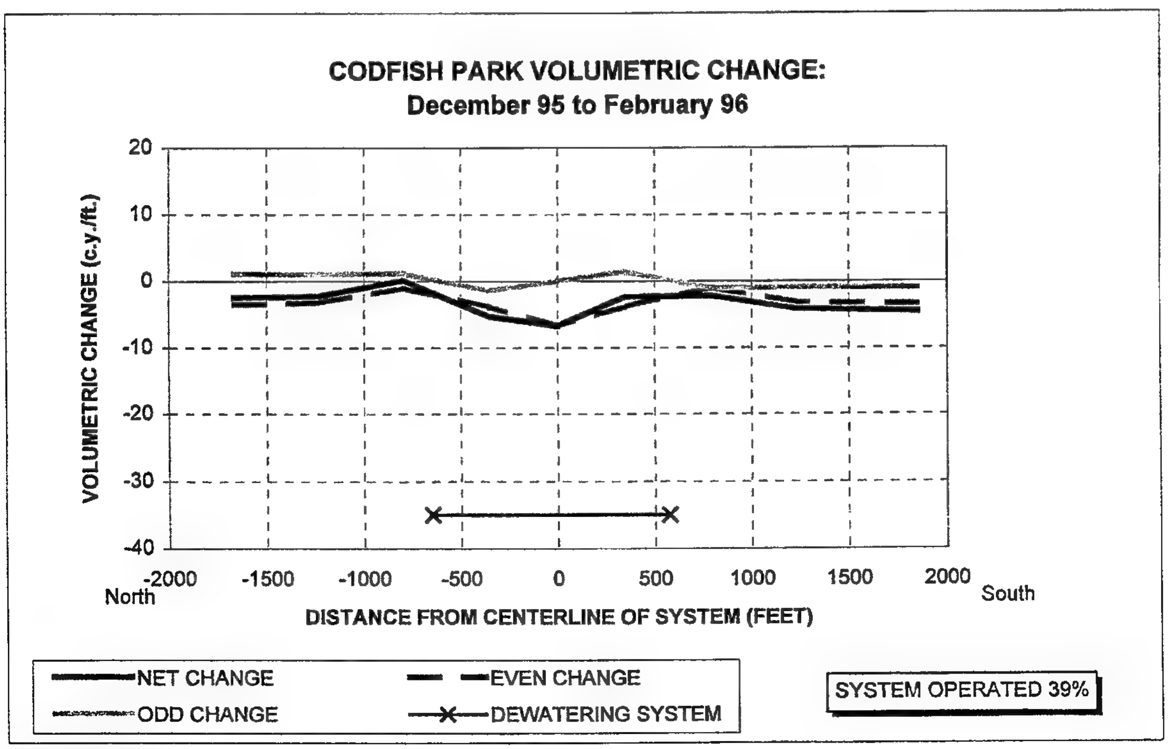

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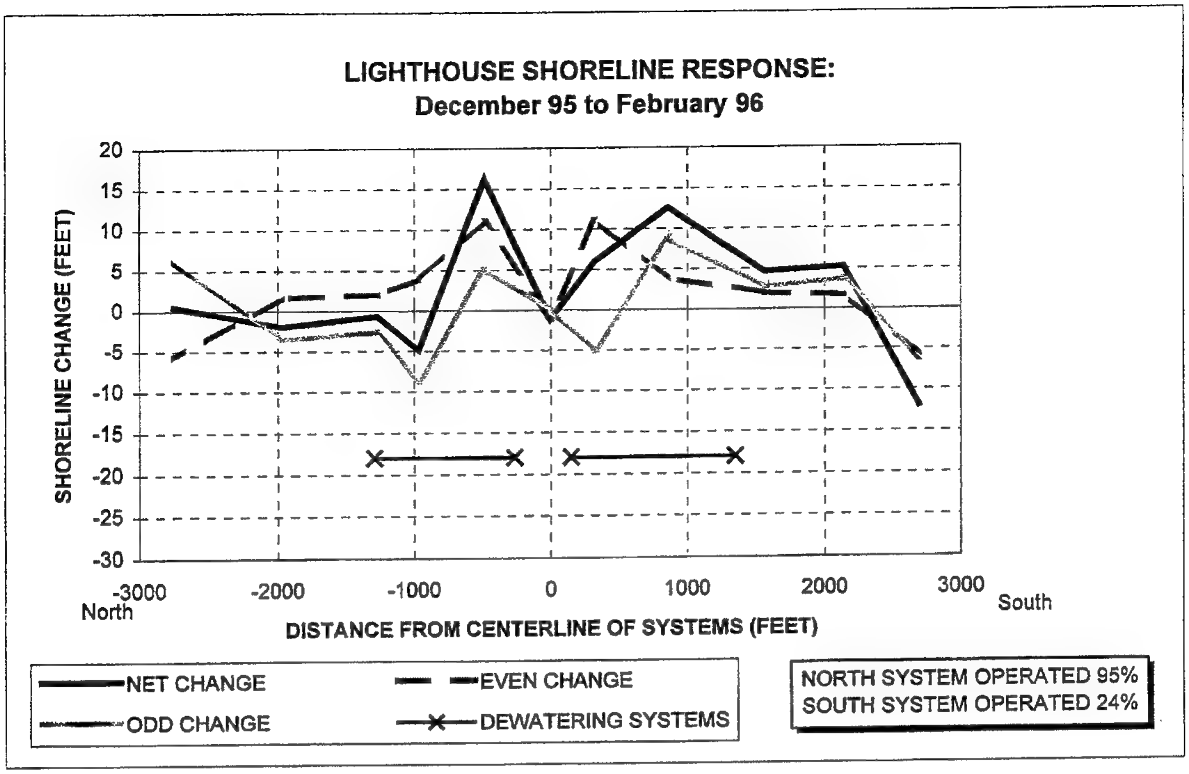

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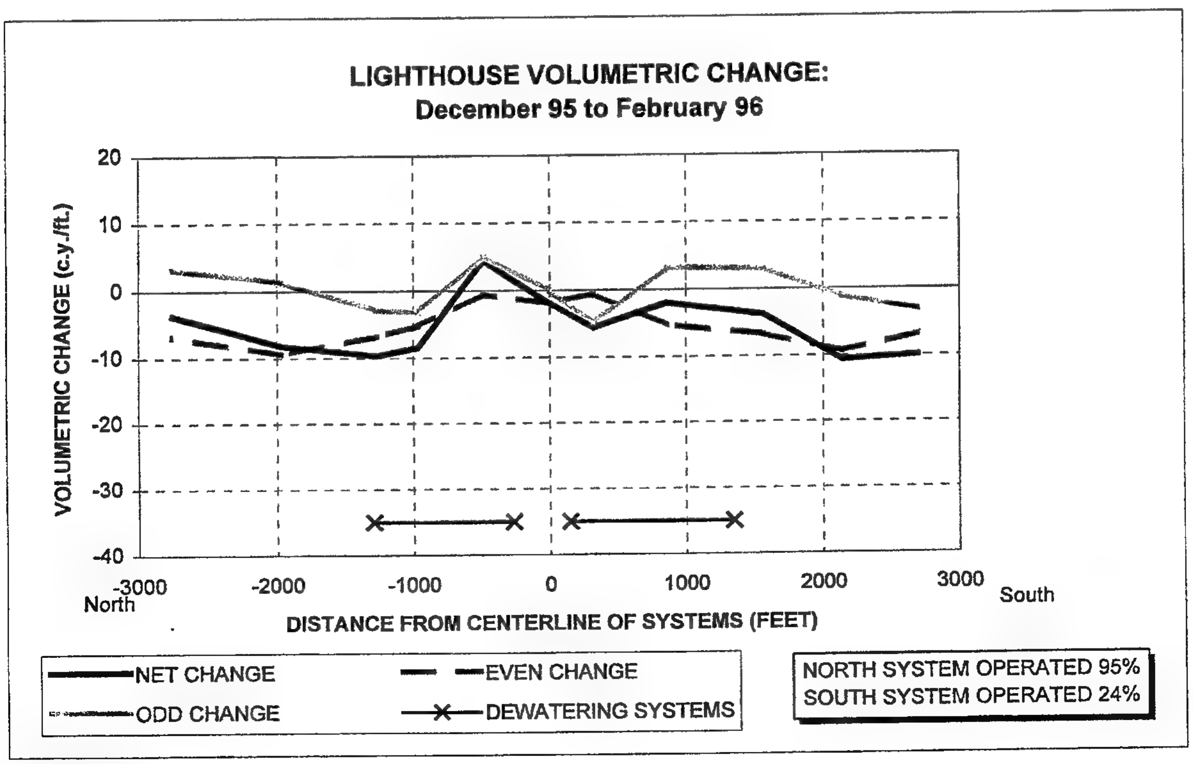

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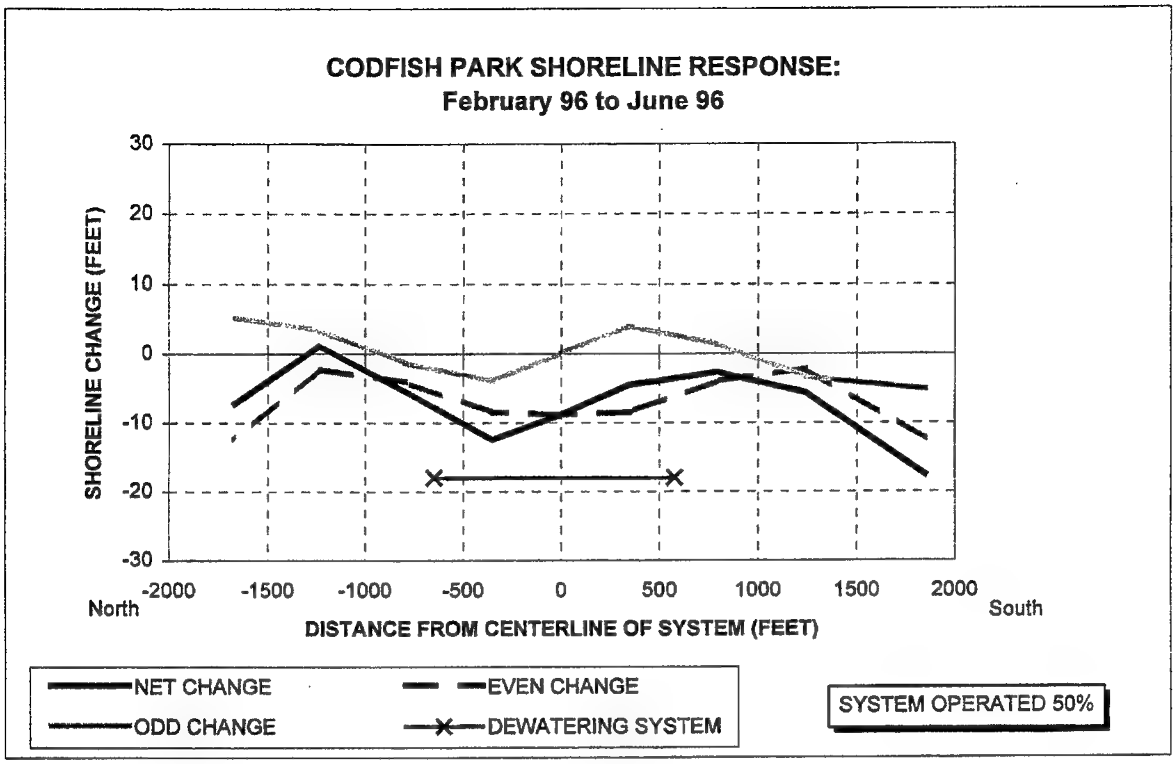

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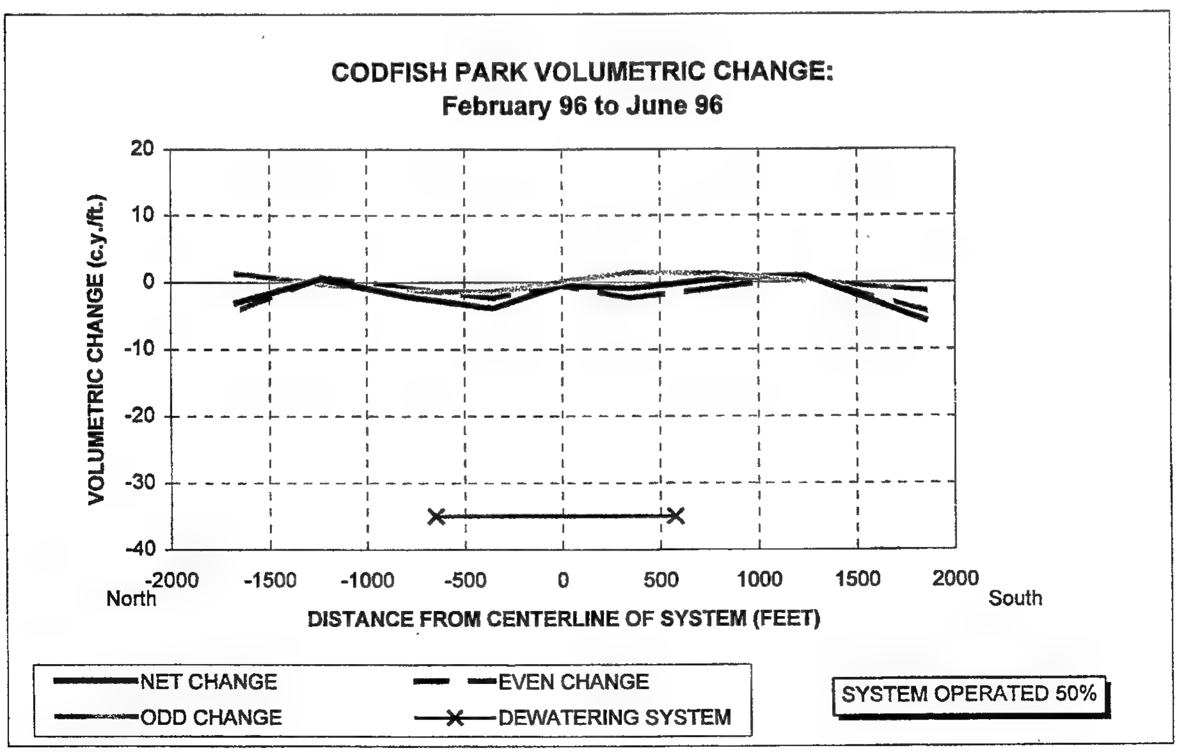

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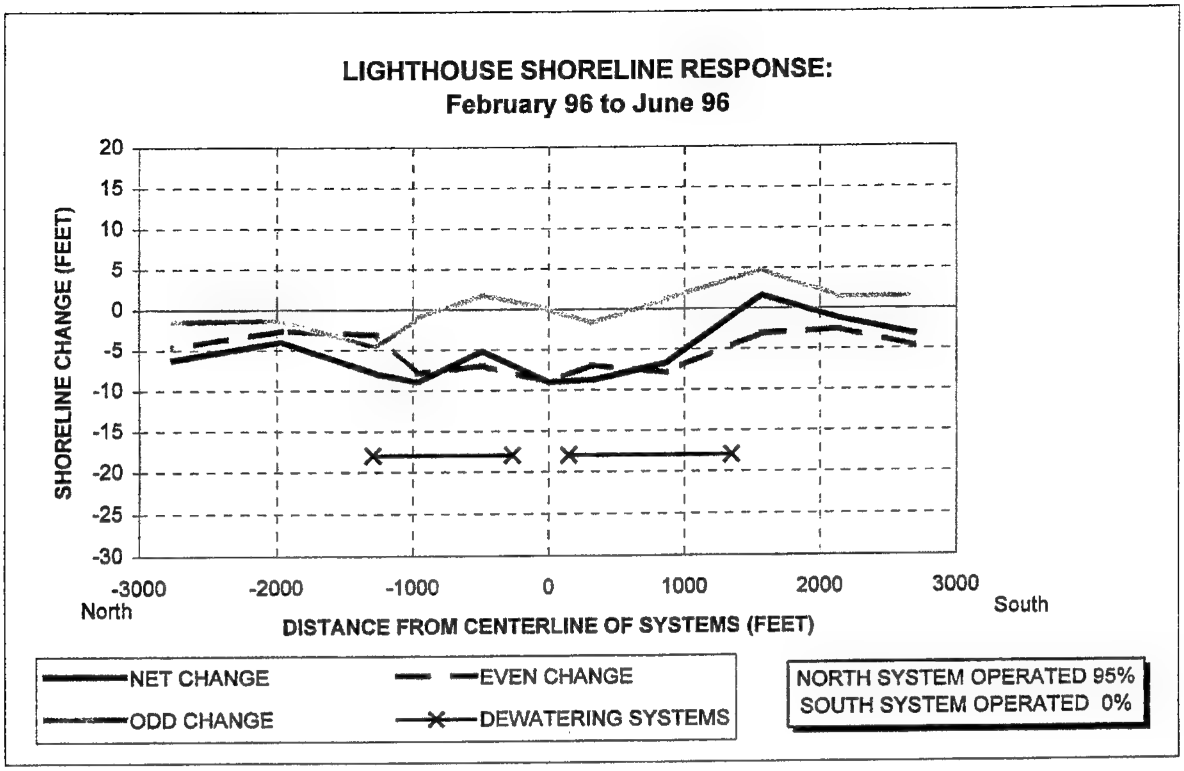

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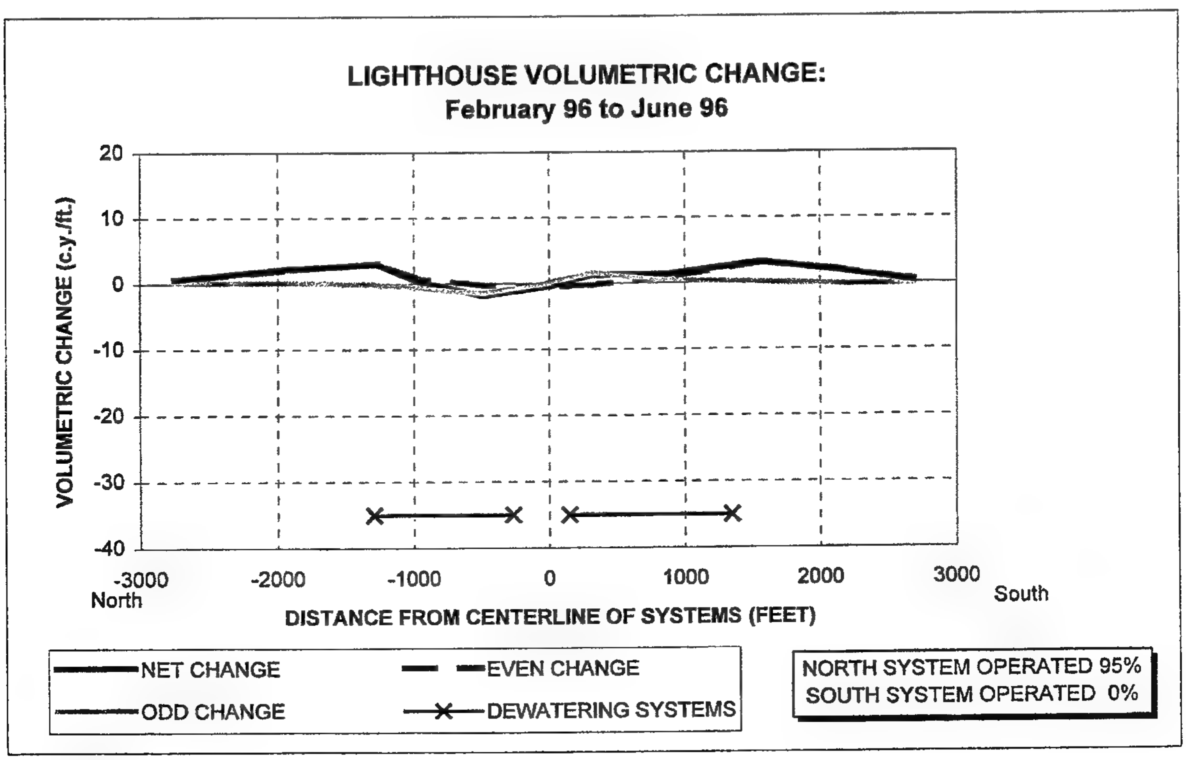
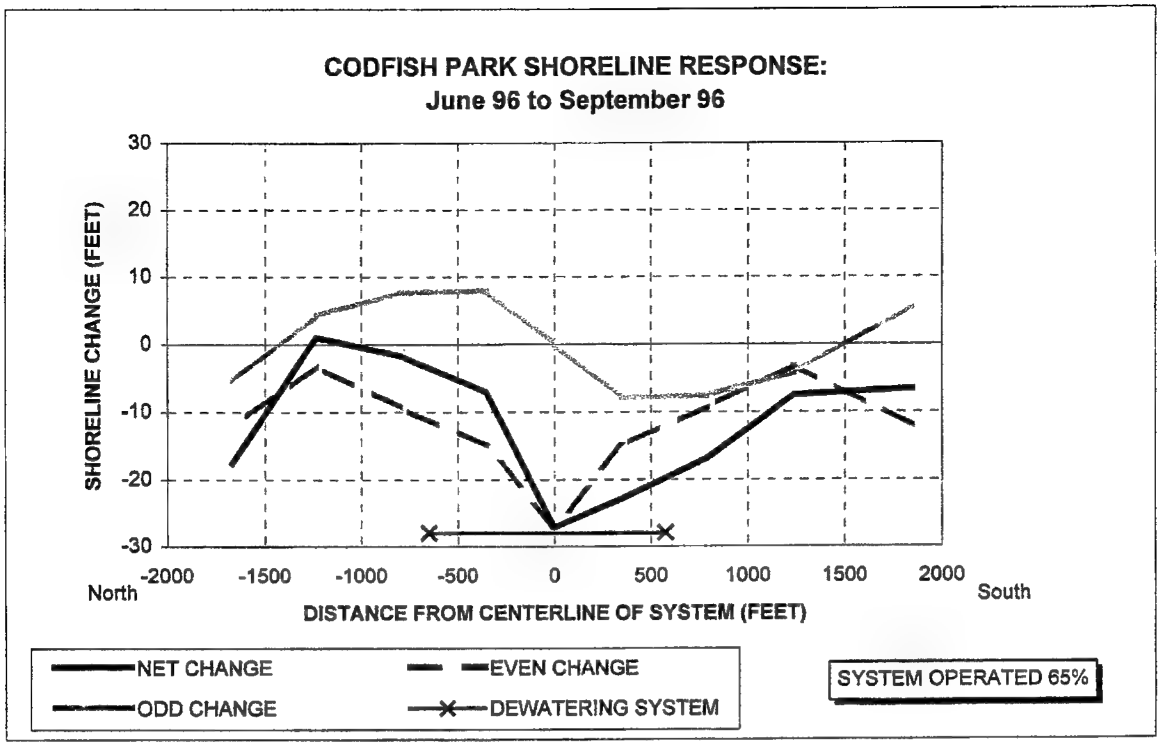


FIGURE 30



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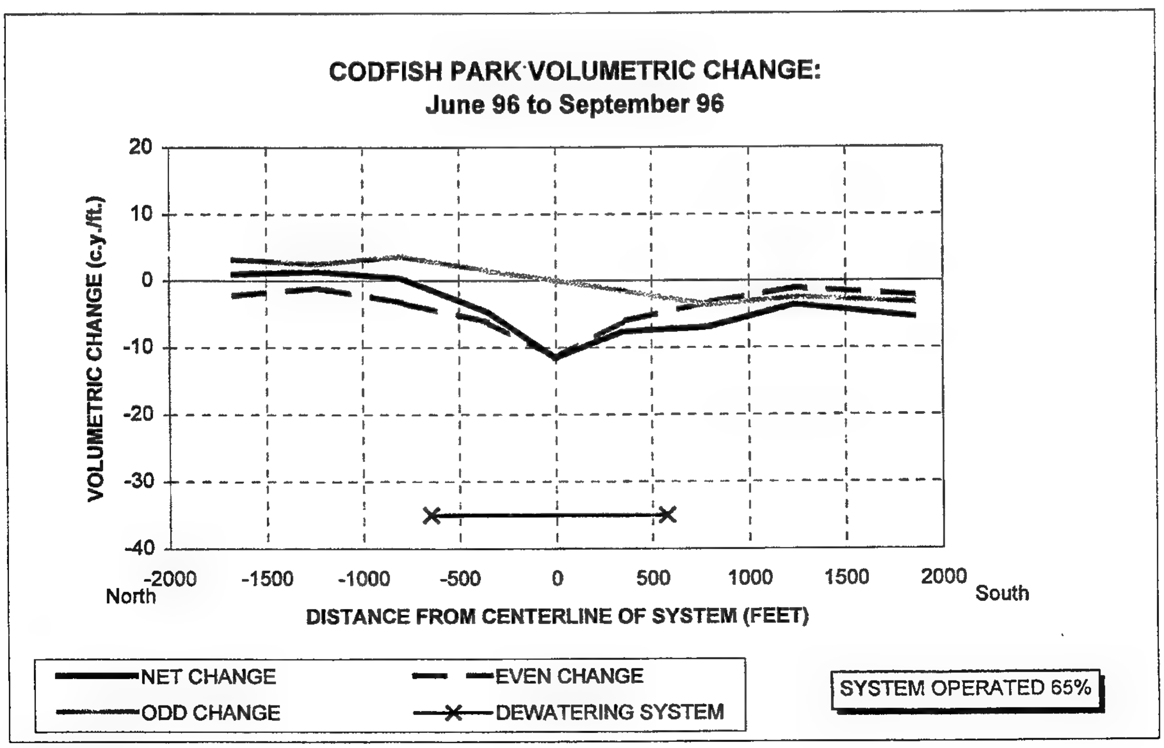

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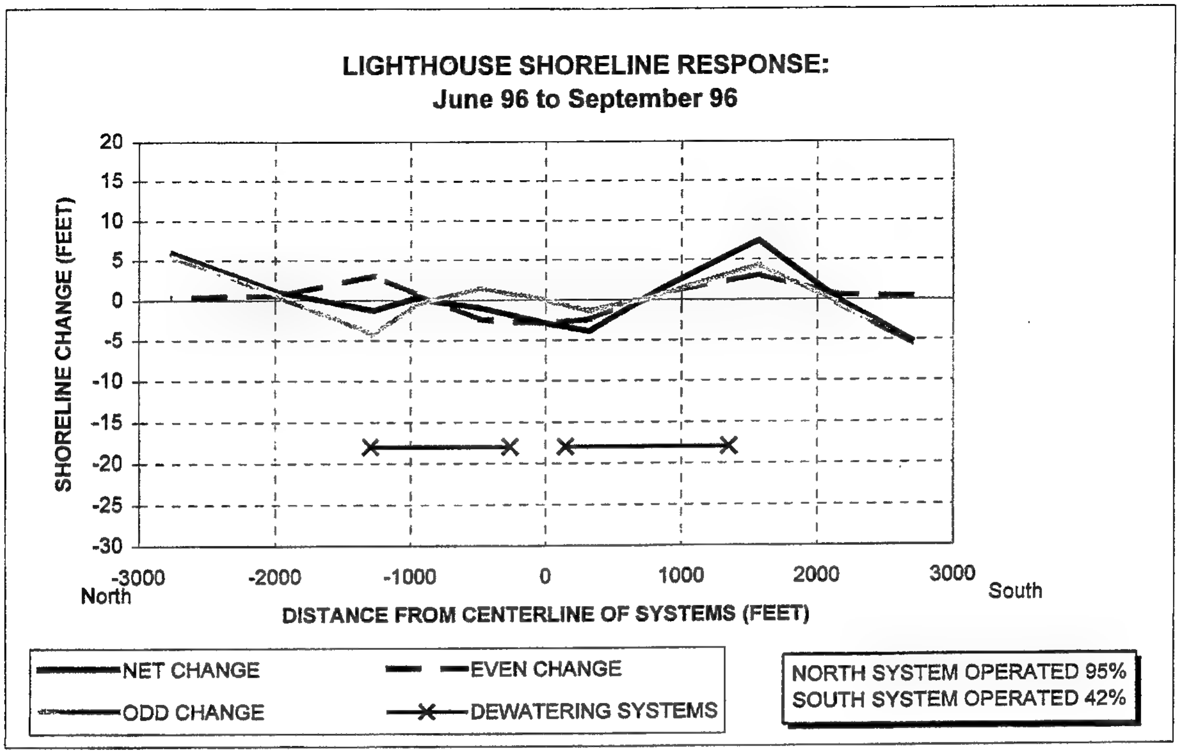

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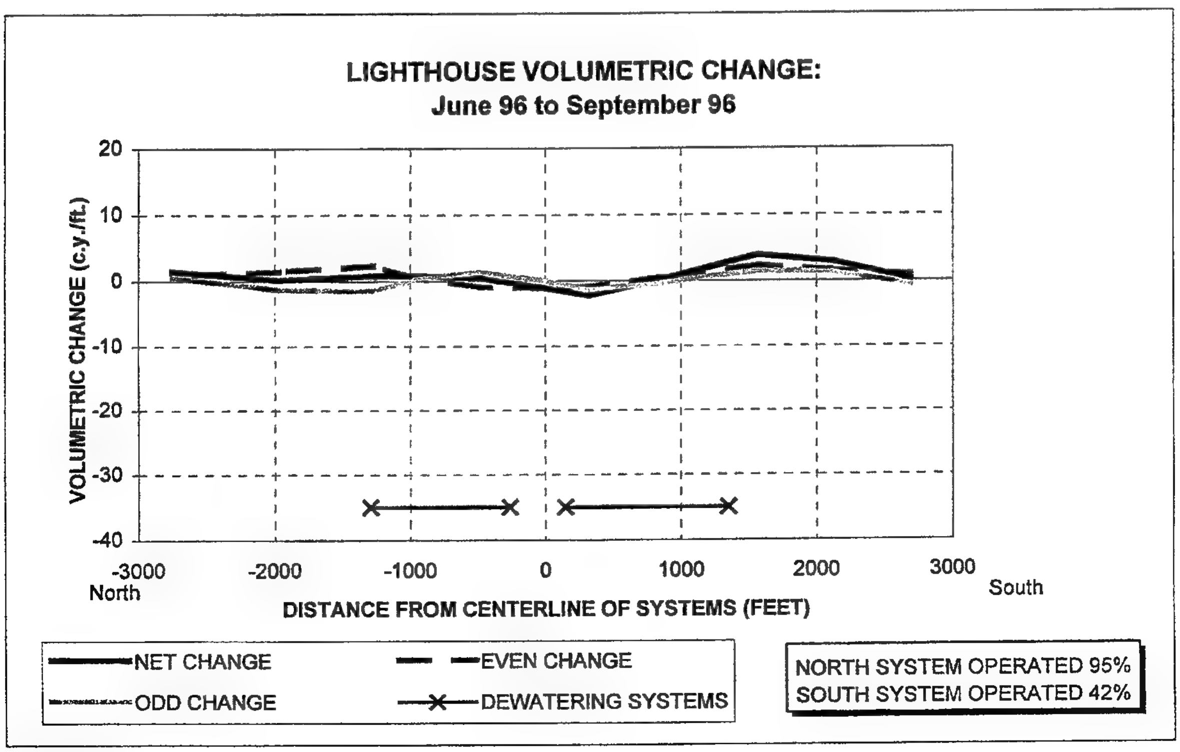
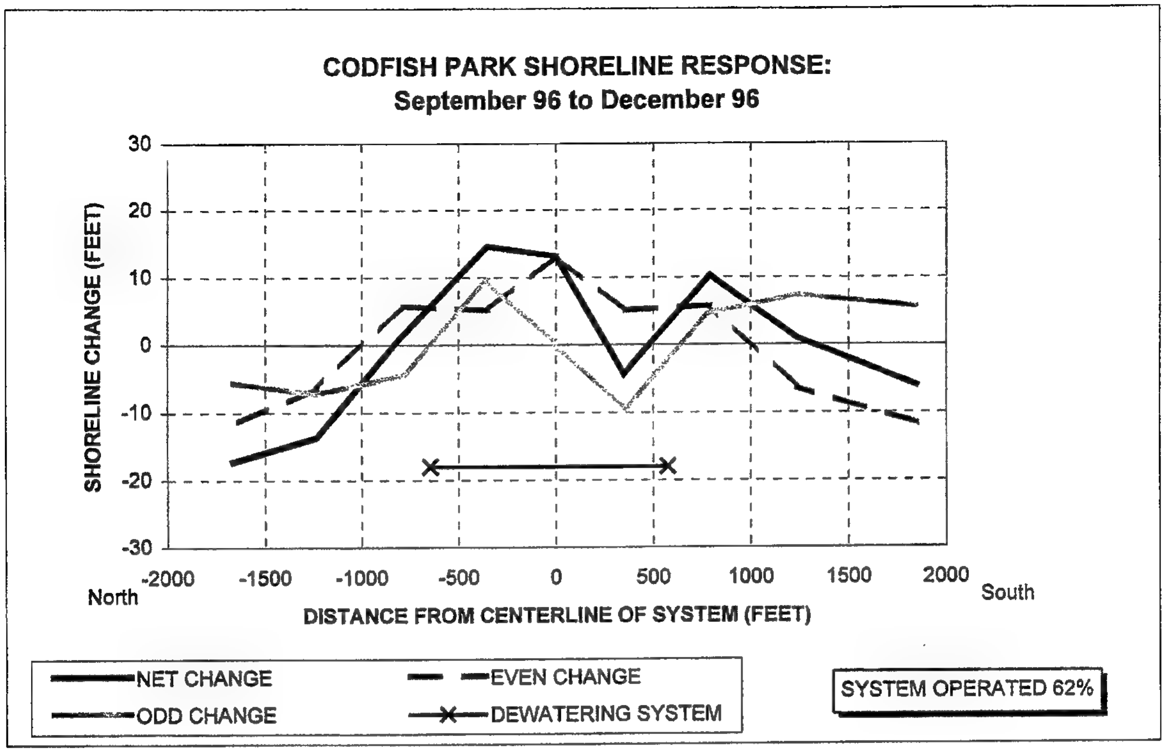


FIGURE 34



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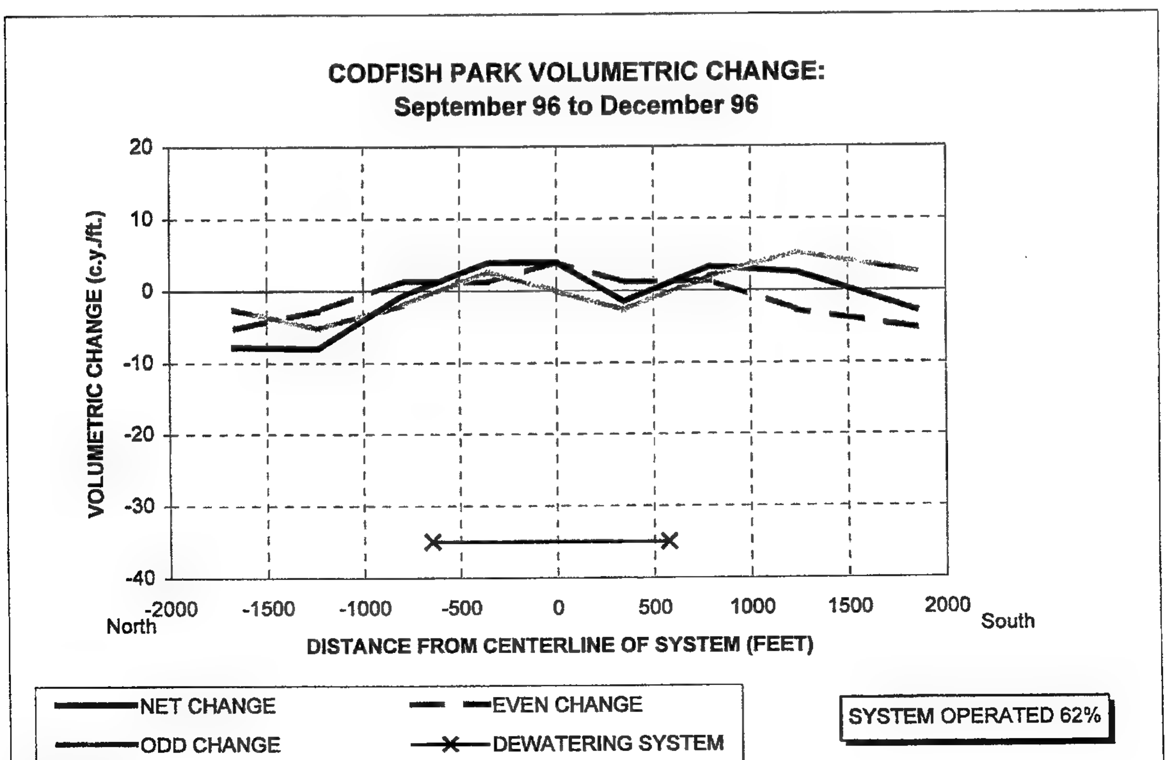

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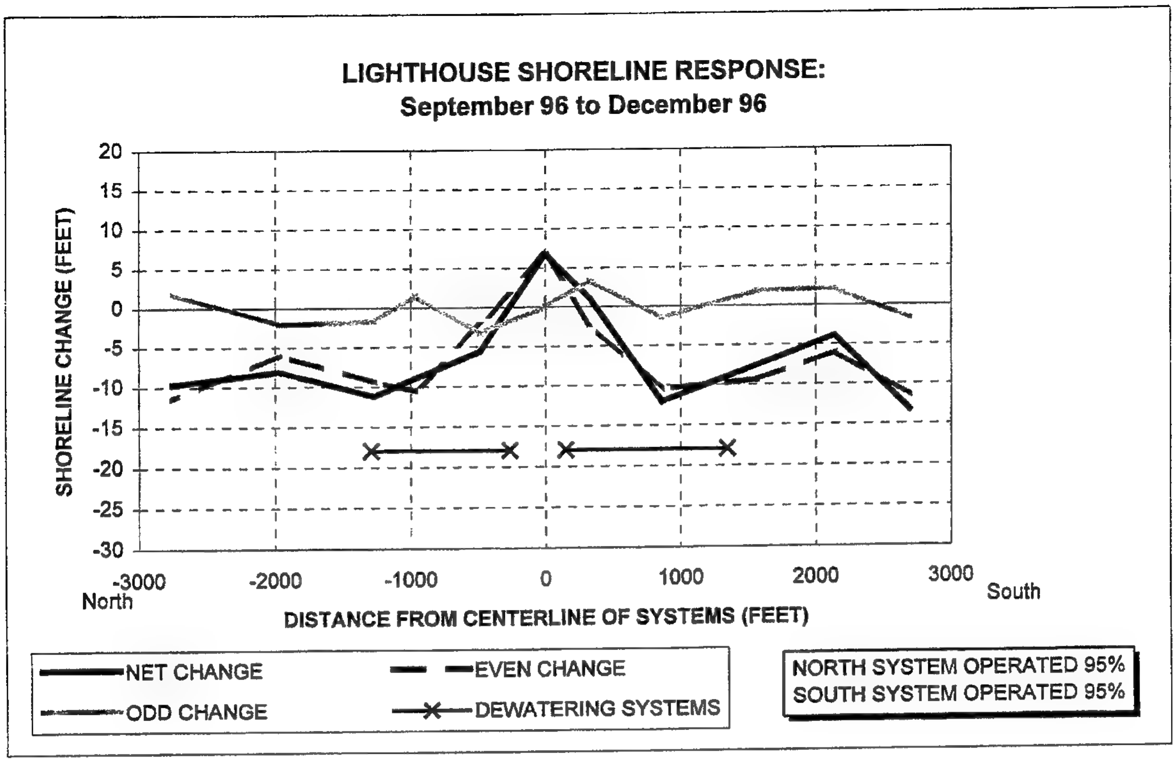
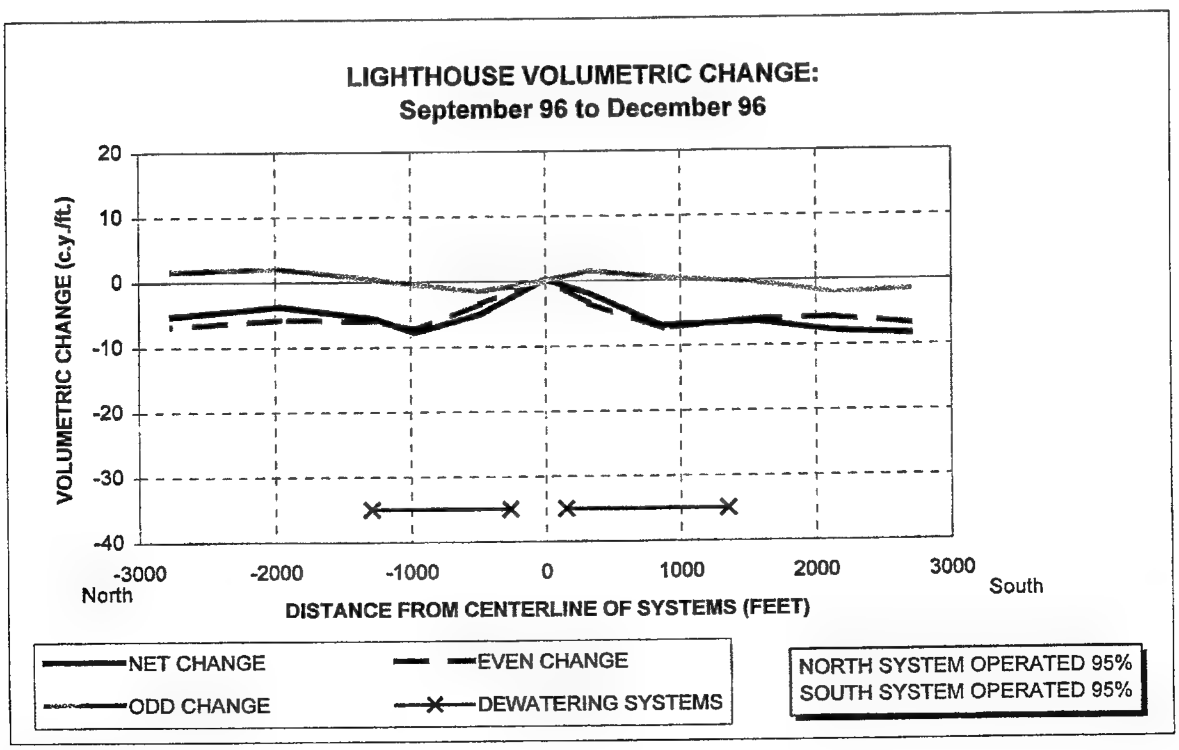


FIGURE 37



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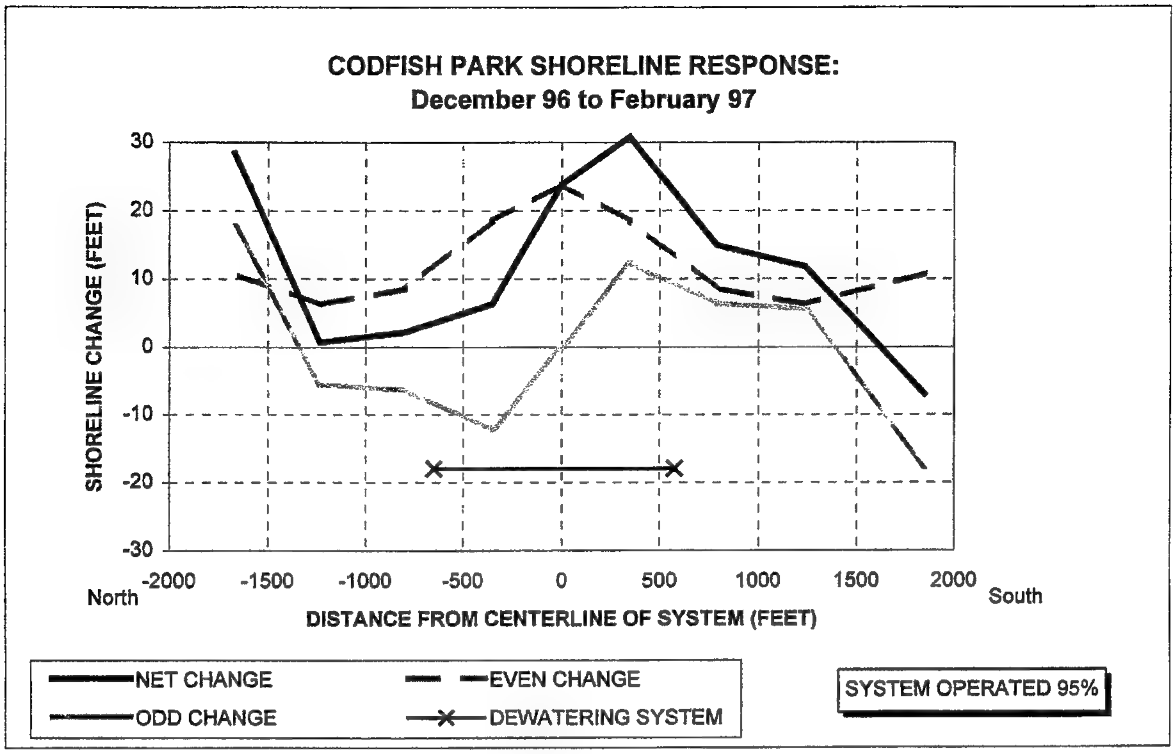


FIGURE 39

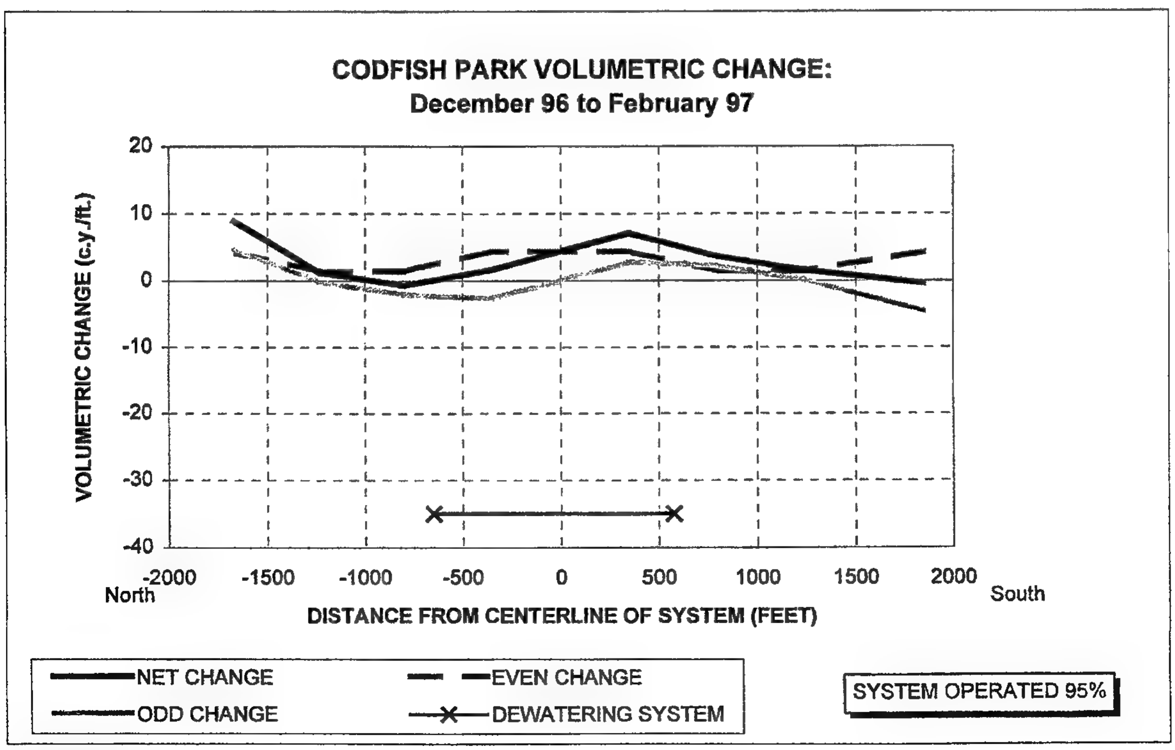


FIGURE 40

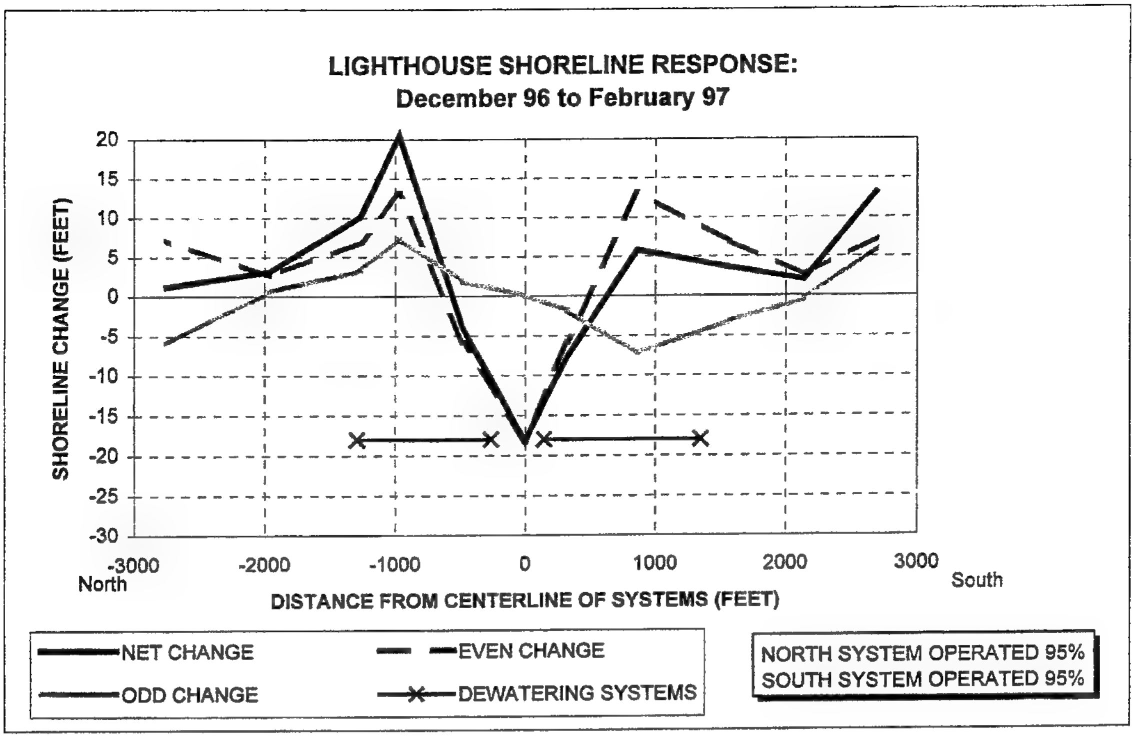


FIGURE 41

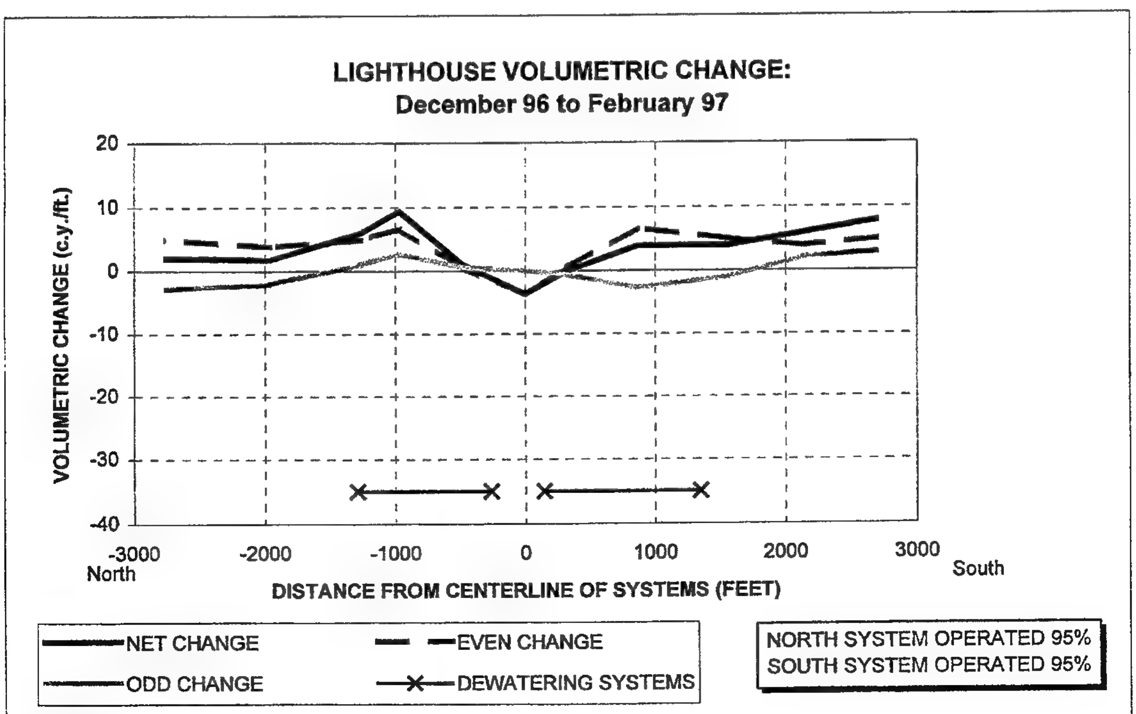


FIGURE 42

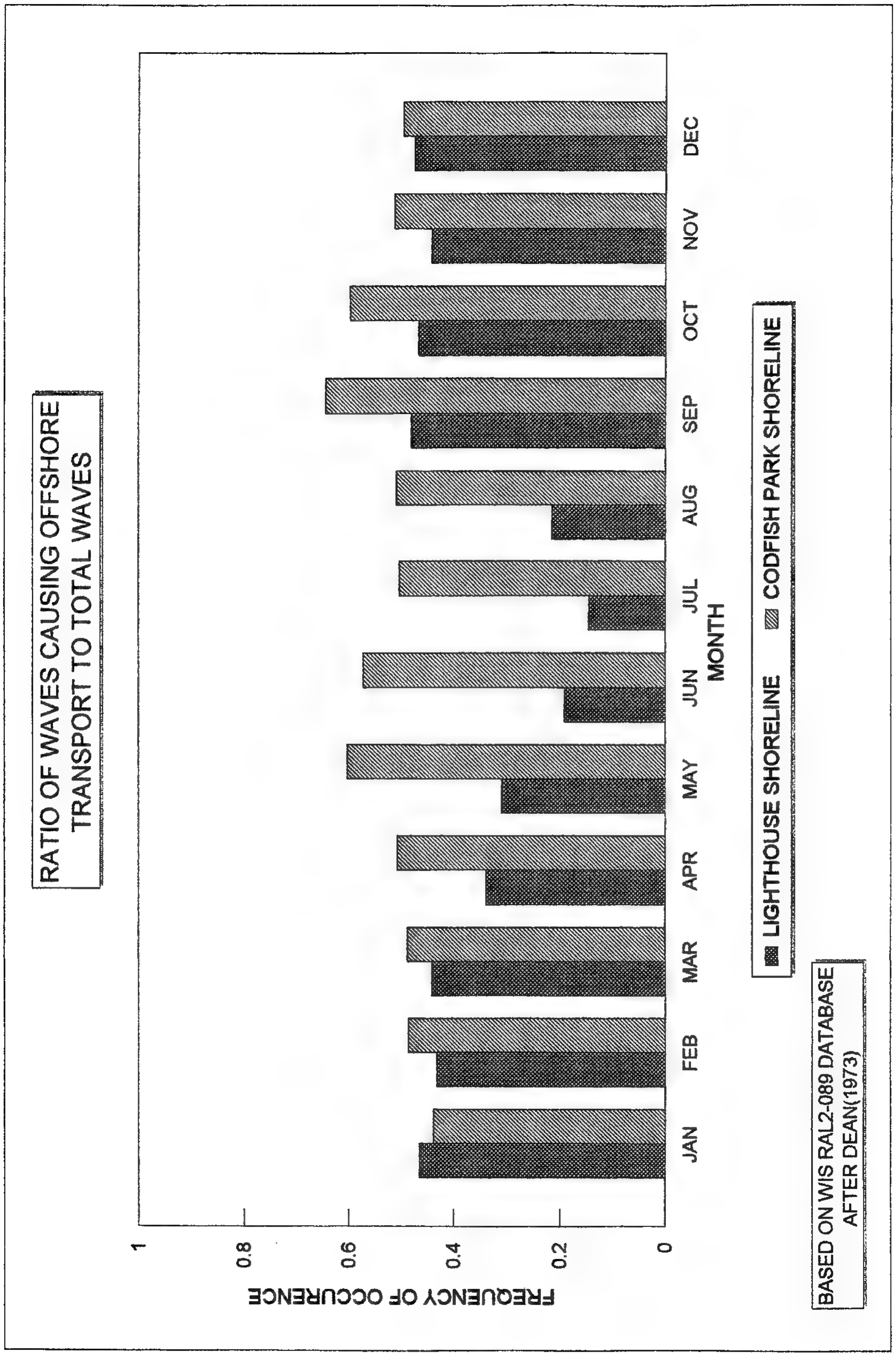
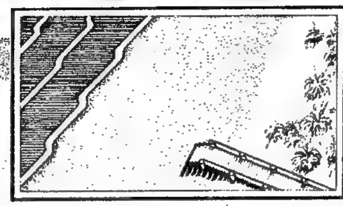

RATIO OF WAVES CAUSING OFFSHORE
TRANSPORT TO TOTAL WAVES
FREQUENCY OF OCCURRENCE
1
0.8
0.6
0.4
0.2
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH
LIGHTHOUSE SHORELINE
CODFISH PARK SHORELINE
BASED ON WIS RAL2-089 DATABASE
AFTER DEAN(1973)

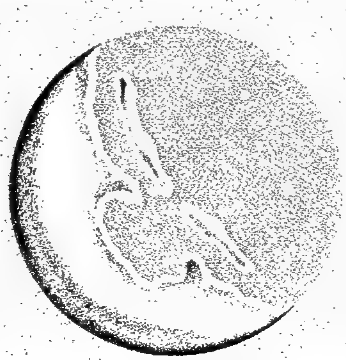
FIGURE 43

Appendix B
System Advertising Brochure
by
Coastal Stabilization, Inc.

Stabeach



The cost-effective, long-term solution for stabilizing America's beaches.



Stabeach

STABEACH Stabilizes Beaches By Enhancing Accretion and Reducing Erosion.

STABEACH is a revolutionary new method of beach stabilization which enhances natural accretion of sand while retarding erosion at about one-half the cost of conventional techniques.

The advantages of the STABEACH System are performance and environmental compatibility. STABEACH helps recover from storm induced erosion without reconstruction. The same processes that built the original beach are utilized to rebuild the beach eroded by high waves.

Other methods can increase turbidity and bury local flora and fauna under many inches of sediment, and may need to be repeated periodically. STABEACH uses slow, natural processes without negative effects on the environment.

Seawalls and revetments may actually harm the beach. Recent studies have shown that on chronically eroding beaches, installation of seawalls or revetments may result in the narrowing or complete loss of the beach. STABEACH is specifically designed to stabilize a wide recreational and protective beach.

Groins and jetties may be effective temporarily in trapping sand along a beach, but have often starved downstream beaches by blocking and forcing offshore the longshore littoral drift. STABEACH does not, and may even help nourish downstream beaches.

STABEACH Offers Stable Protection At Lower Cost.

STABEACH costs about half of conventional programs when amortized over 20 years. Although each beach offers a different challenge – and opportunity – a typical cost per mile for installation is approximately $250 per linear foot, or $1,320,000. Annual operation and maintenance is estimated at an average of $16 per foot, or $85,000 per mile. Assuming a 10 percent interest rate and a five percent increase in annual operation cost, the present value of installing, operating, and maintaining a one-mile STABEACH System for a period of 20 years is approximately $2.4 million.

Coastal Stabilization now offers a reasonably priced, environmentally favorable alternative to traditional methods of beach erosion stabilization with its STABEACH System. If your beach suffers chronic erosion problems, contact the coastal contractors at Coastal Stabilization, Inc.

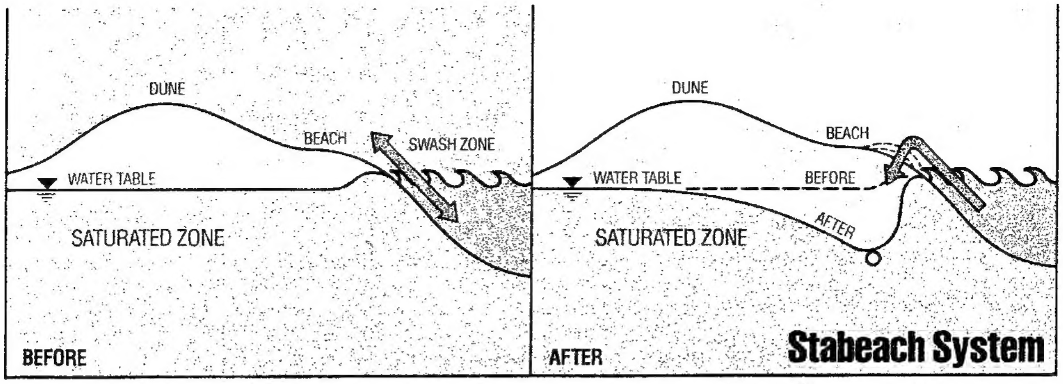
STABEACH Uses Proven Theory and Technology.

Moretrench American Corporation, Coastal Stabilization's parent company, has long been a leader in dewatering technology, and the theory behind the STABEACH System has been researched for nearly 50 years by noted coastal scientists and engineers. The STABEACH System has been working well in Florida since September 1988.

STABEACH Is Already Working in America.

The first STABEACH System was installed at Hutchinson Island, near Stuart, Florida, in August and September 1988. The completed installation was activated in the second week of September. Results of monitoring the beach in front of the site during the summer and fall of 1988 and through January 1989 indicate that the treated beach has retained its summer-time characteristics and that in fact, it is as much as 30 feet wider than in July of 1988. Untreated control areas to the north have lost between 30 and 40 feet of beach width. Immediately to the south, the untreated beach has gained about 20 feet in width.

Monitoring to date indicates a strong connection between the lowered water level under the beach and the stabilization of the beach treated with the STABEACH System. Accumulation of sand south of the STABEACH installation is thought to be a positive impact of the system. The treated beach retains the characteristics of a wide summer beach. It is expected to remain so during the entire winter erosion cycle.



STABEACH Works Simply . . . And Well.

When beach sands are saturated with water, such as during an outgoing tide on an untreated beach, each wave is more likely to wash sand away than it is to leave sand behind. This process typically occurs during strong waves of winter and during summer storms, leading to beach erosion.

Since between 8,000 and 12,000 waves may strike the surface of a given beach during a typical 24-hour period, natural processes which lead to rapid beach erosion may be transformed into beach accretion, by using the STABEACH System.

A specially designed drainage system is installed under the beach, completely out of sight. The drains are connected by underground piping to a pumping well landward of the beach, generally behind the dune. Pumps in the well remove groundwater from under the beach and discharge it into the ocean, bay or a convenient canal. The result is a continuously lowered water table under the beach.

When the water table under the beach is lower than the water level of the ocean, beach accretion is enhanced and beach erosion is reduced.

As each wave rushes up the beach, water from the wave easily drains through the dry beach, leaving part of its suspended sands in the wave on the beach. Less water runs back into the ocean and less sand goes with it, thus reducing the potential for erosion. Moreover, as the water percolates through the beach, it compacts and densifies beach sands, making them more erosion resistant. The result is greater accretion and less erosion.

STABEACH May Help Save Your Beach, Too.

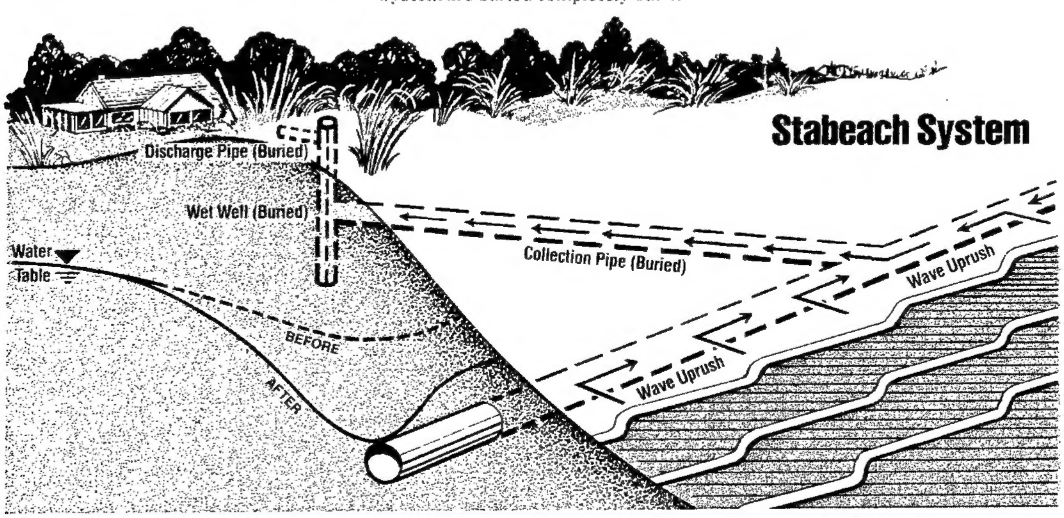
Although the STABEACH System will not work on every beach, many beaches in America may benefit from application of this revolutionary new technology.

Environmental permits are required in most states, and are decided on a case-by-case basis. Coastal Stabilization's review of the performance of the Hutchinson Island site has not identified any conflicts which would present an obstacle to obtaining additional permits.

Given reasonable maintenance, the STABEACH System should enjoy a long life similar to water well and commercial dewatering systems which use similar technology and have been in continuous use for many years.

All components of the STABEACH System are buried completely out of sight and hearing, and do not interfere with natural aesthetics. STABEACH submerged pumps are run by electricity and are very quiet.

In summary, the STABEACH System is the cost-effective application of a thoroughly researched and proven technique for beach preservation and enhancement. Contact Coastal Stabilization, Inc. to see if your beach may be preserved using the STABEACH System.



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13. ABSTRACT *(Maximum 200 words)*

This study documents the use of beach dewatering systems to accrete beach sand and minimize erosion, and to develop quantitative guidance for constructing and operating beach dewatering installations. The study describes three independently operating dewatering systems deployed along the eastern shore of Nantucket Island, Massachusetts, and the field monitoring program established to study the influence of the system on beach processes. The monitoring program included measurements of beach morphology and hydrogeology, nearshore bathymetry, meteorology, system operation and maintenance, discharge water quality, and the effects on beach vegetation and meiofaunal communities.

The ecological and environmental assessment of the influence of the dewatering systems on Nantucket revealed that the systems had a minimal effect on ocean water quality and quality of the local freshwater aquifer. The observed changes in maritime vegetation and the inter-tidal invertebrate communities could not be attributed to system operation. However, it is advisable that potential environmental impacts be assessed in detail for future installations. A simplified modeling exercise to determine the aerial influence of system drawdown at Codfish Park revealed that the landward extent of drawdown is considerably greater than the longshore extent. Landward extent of drawdown may have adverse ramifications if the local groundwater is exploited as a public water supply, or if septic systems are within the system's influence.

14. SUBJECT TERMS

Accretion	Dewatering systems
Beach processes	Drawdown

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